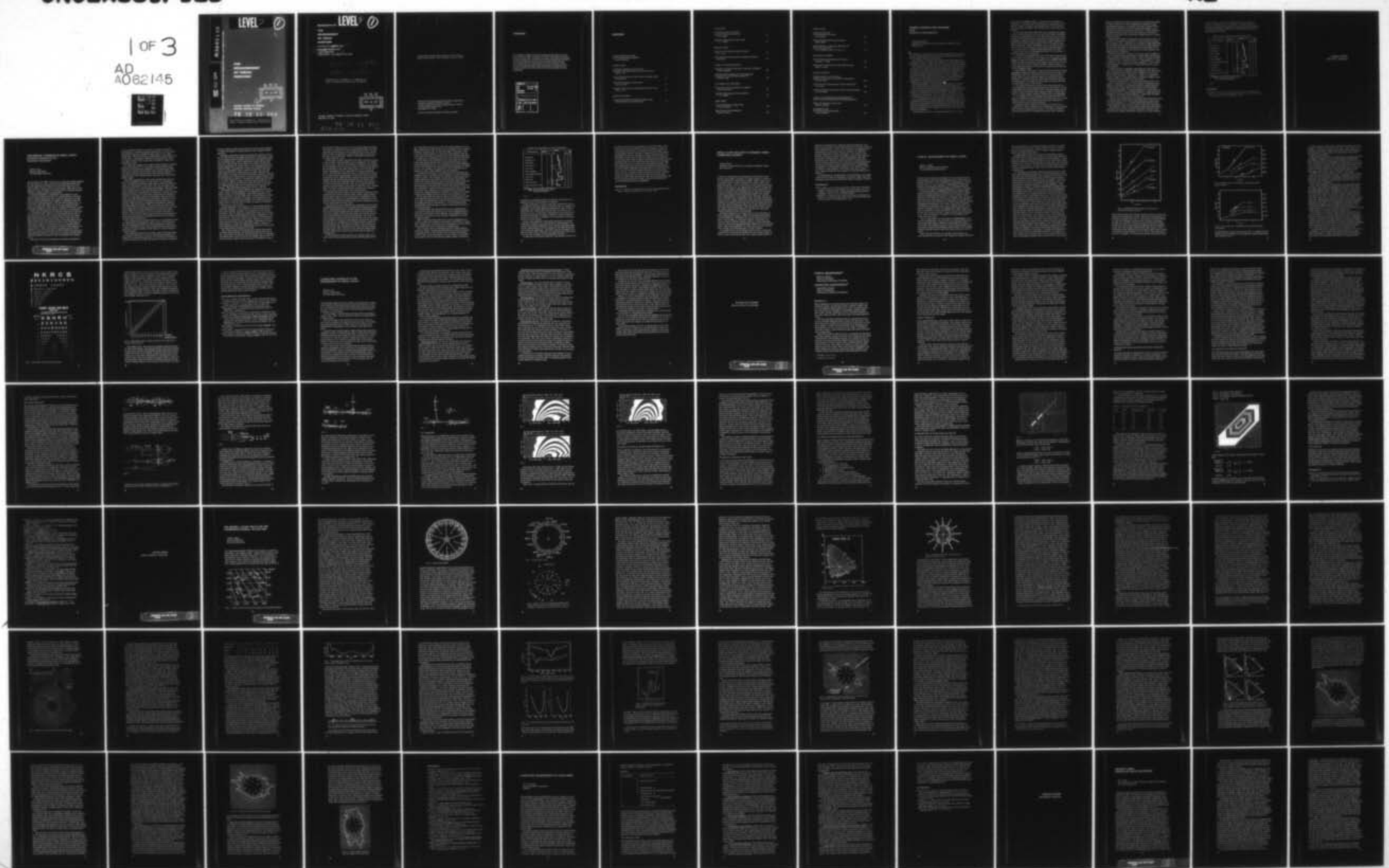
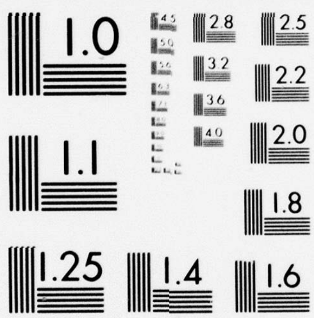
AD-A062 145 ARMED FORCES-NRC COMMITTEE ON VISION WASHINGTON D C F/G 6/16
THE MEASUREMENT OF VISUAL FUNCTION PROCEEDINGS OF SPRING SYMPOS--ETC(U)
1968 M A WHITCOMB, W BENSON NONR-2300(05)

UNCLASSIFIED NL

1 OF 3
AD
A062145




1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

LEVEL II

1

SC

EDITED BY MILTON A. WHITCOMB AND WILLIAM BENSON/ARMED FORCES—NRC COMMITTEE ON VISION

THE MEASUREMENT OF VISUAL FUNCTION

NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL

LEVEL II

1

Symposium on THE MEASUREMENT OF VISUAL FUNCTION

6

Proceedings of Spring ~~Meeting~~ Symposium, 1965

10 ~~Edited by~~ MILTON A. WHITCOMB
and WILLIAM BENSON
ARMED FORCES — NRC COMMITTEE ON VISION

11 1968 12 253p

15 Nonr-2300(05)

Distribution Statement A: Approved for public release; distribution unlimited.

NATIONAL ACADEMY OF SCIENCES — NATIONAL RESEARCH COUNCIL
Washington, D. C., 1968

Reproduction is sponsored by Contract No. NONR 2300(05)
between Armed Forces - NRC Committee on Vision and ONR

Inquiries concerning this publication should be addressed to:
Armed Forces-NRC Committee on Vision
National Academy of Sciences—National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Library of Congress Catalog Card Number 68-60081

FOREWORD

In the Spring of 1965 a two-day meeting was held under the auspices of the AF-NRC Committee on Vision. The papers presented at this meeting were concerned with ideal and practical techniques for the measurement of each of the selected visual functions. The interest shown in these papers by visual scientists and by practicing ophthalmologists and optometrists prompted the Executive Council of the Committee on Vision to provide for their publication.

CONTENTS

GENERAL INTRODUCTORY REMARKS by the Chairman of the Symposium

Arthur Jampolsky
Institute of Visual Sciences, Presbyterian Medical Center
San Francisco

The purpose of this meeting is to provide a basis for re-evaluating the testing procedures for each of the different visual parameters useful in visual classifications.

The laboratory methods of assessing each visual function are presented in order to update the awareness of all possible testing techniques available in assessing the considered visual parameter.

The clinical presentations are directed toward assessing those techniques best suited for practical utilization in measuring the considered visual parameter by (a) professional personnel, (b) non-professional (technical) personnel, and (c) machine or semi-automated methods. Special reference is made to updating techniques such as the utilization of electrodes, machines (orthorator types), and other semi-automated techniques capable of quantifying or scaling the test scores.

Where appropriate, comments are made relative to training of the visual function, and predictability of change with age.

The material presented provides a basis for making judgments relative to the preferred testing techniques best suited for the needs of the different agencies and services requiring visual classification and testing. These conclusions are derived from, or compared with, the array of laboratory techniques available.

It is realized that the division into the laboratory and clinical presentation aspects is purely arbitrary. All authors have been judiciously selected because each possesses all of the distilled virtues of both clinical scientists and scientific clinicians. They have been asked merely to assume some biases for purposes of their presentations.

The present goal is not concerned with needs, uses or pur-

poses, limits, standard setting, or necessity for validation of standards, or whether vision is important or unimportant to any specific simple or complex performance task. The concern is with the testing techniques most suitable for scoring and classification.

A few words about the background of the problem seem appropriate. Working Group 20 of the Armed Forces-NRC Committee on Vision re-evaluated some of the aspects of the visual requirements for flying and made some general conclusions and recommendations regarding visual requirements, visual standards for performance tasks in general, and the role of the visual scientists in assessing visual capabilities, and in assisting the agencies and services with their needs for visual classification systems. This report is available (Jampolsky & Morris, 1964).

Some of the main recommendations which are of relevance to this symposium were as follows:

1. To state the capabilities in each of the major visual parameters (acuity, heterophoria, color vision, etc.) in grades of visual fitness in order to augment and amplify the usefulness of present visual classification systems. Such grades and grade decrements could serve as a basis on which a flexible, dynamic system of visual standards could be constructed and appropriately adjusted to meet changing needs.

2. To create a "core team" composed of (a) operational-visual specialists, each representing various Armed Service and civilian agencies, who are concerned with visual requirements for flying, and (b) visual scientists, expert in a particular visual parameter, selected to join the team at the time their specialty is being graded. The grades of visual fitness concept could best be executed by such a "core Team."

3. To define "perfection" in each of the visual parameters. Ten graded decrements signifying fitness less than perfect could be specified below the top grade level. Upon this matrix, the different criteria of selection and retention could be clearly specified, or a visual profile could be constructed for any individual.

4. To assign to the team grading each visual parameter the task of evaluating the present tests employed by the services and agencies, and to recommend improved testing techniques for both machine and non-machine methods.

This report was accepted by the Executive Council of the Committee on Vision, and after due consideration, it was decided that it would be appropriate to devote a Committee meeting to the specific purpose of evaluating the present tests employed,

and to re-examine the visual parameters to be tested and graded in order to aid the core team, augmented by experts in each considered parameter, to establish the grades of visual fitness. The numbers attached to the test results are numbers per se without any relevance necessarily to their use. These should be considered labels, and the way in which they are determined should not necessarily be specifically related to the use to which they may be put.

Visual acuity should be assessed for visual acuity's sake. Refractive error should be assessed in order to detect and grade the refractive error. Although one can seldom escape judgmental factors which enter into the decisions relative to tests and grading, such factors should be selected with an eye toward as universal use as possible for classification in static, dynamic, and unknown stress conditions.

How does one test or measure the overall visual capability in order to predict visual performance? Historically, the following visual parameters have been tested in order to satisfy the need: 1. visual acuity; 2. refractive error; 3. heterophoria; 4. ocular rotations; 5. color vision; 6. distance judgment; 7. accommodative amplitude; 8. visual fields; 9. night vision; and 10. intraocular tension.

A disproportion of inattention apparently has been given to other more dynamic conditions, more difficult to test and assess, such as dynamic visual acuity, glare resistance or recovery, photo-stress, detection, tracking, etc. Little or no utilization has been made of electrophysiological methods in applied visual testing techniques, perhaps for good reasons.

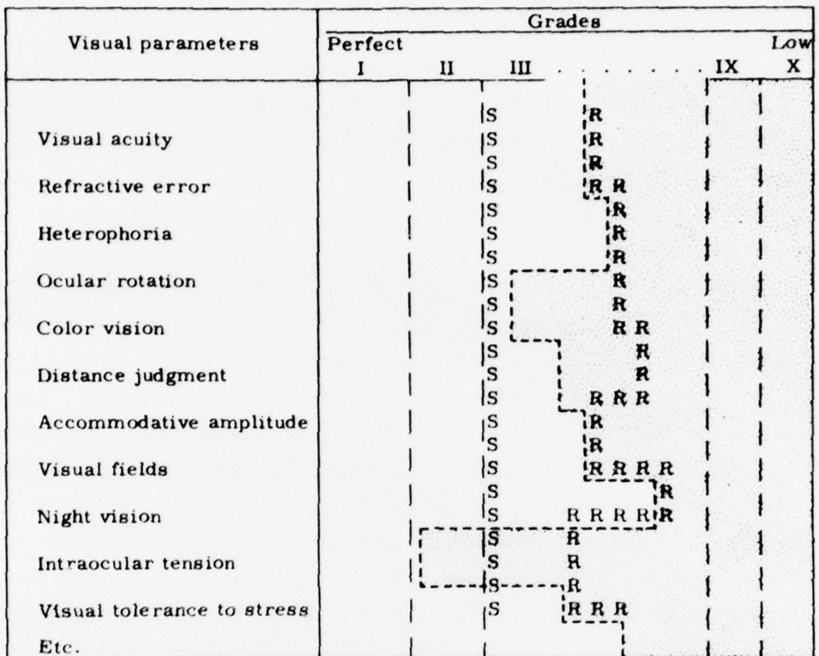
By way of comparison, a cardiovascular testing profile is of interest. This battery of tests under dynamic conditions makes extensive utilization of electrophysiological testing techniques and provocative stress states, and consists of the following: 1. ballistocardiogram; 2. vectorcardiogram; 3. stress-provocative test exercise; 4. prone-supine position; 5. hyperventilation followed by maximal breath-holding; 6. carotid sinus massage; 7. 100 per cent oxygen; and 8. tilt table, etc.

The task should begin with the question of how well do the present visual tests of the selected visual parameters assess overall visual capability, i.e., continued health and integrity of the visual apparatus under normal, dynamic, and stress conditions.

The request to make such practically useful but compromised judgments, derived from scientific laboratory methods, sometimes elicits a sudden conditioned reaction in a certain segment

of the scientific community. Fortunately, the Committee on Vision is structured so as to facilitate a seasoned response to the practical needs of the agencies and services based upon both laboratory and clinical experiences. This symposium reflects these purposes and goals.

Example of the Proposed System for Grades of Visual Fitness



Note: SSSSS selection requirements for service X
RRRRR retention requirements for job X
----- visual profile of subject Z

FIG. 1.

REFERENCE

Jampolsky, A., & Morris, Ailene. Visual requirements for flying: some aspects of re-evaluation. Washington: Armed Forces - NRC Committee on Vision, Report of Working Group 20, 1964.

VISUAL ACUITY

Glenn Fry, Chairman

PRELIMINARY COMMENTS ON VISUAL ACUITY
Introductory Statement by the Chairman of the Section

Glenn A. Fry
School of Optometry
The Ohio State University

The Armed Forces-NRC Committee on Vision has already adopted the test charts for visual acuity involving the Sloan letters and has also approved the Bausch and Lomb Ortho-Rater as a machine method of making acuity measurements. Under the circumstances, it does not appear to be appropriate to propose alternate methods of making acuity measurements.

It may be desirable to reformulate the standards in more general terms without reference to a specific device. The Sloan letters could be designated. One could then specify the arrangement into lines with each line containing a specified number of letters and a specified spacing, contrast and luminance level. It may be that the Ortho-Rater may be the only instrument that meets the standards in mind, but the standards themselves should be capable of being specified without reference to a trade name.

In accordance with the recommendation made by Dr. Ogle and his committee, (Ogle, 1953) it is recommended that the size of the letters on the test chart be specified in terms of the visual angle subtended by the critical detail, which in the case of the Sloan letters is the width of the strokes. The total height of each letter is five times the width of the stroke. The visual angle is specified in minutes. An alternative way is to specify the size of the letter in terms of the distance at which it will subtend five minutes of arc. Still a third way of specifying the size of the letters is in terms of the Snellen fraction in which the numerator represents the distance at which the test is made, and the denominator the distance at which the letters subtend at five minutes of arc.

The sizes of the letters included on the chart are graded in

terms of uniform steps on a log scale. Dr. Ogle considered three things in connection with his justification of the use of the logarithmic scale for grading the letter sizes on the visual-acuity chart. The first of these considerations is that if the area of the letter is specified as opposed to the height of the letter, the steps in area as well as the steps in height are linear on a logarithmic scale.

Dr. Ogle also considered the experimental evidence in support of the notion that there is a logarithmic relationship between diopters of myopia and the logarithm of the visual angle which can just be resolved. On the basis of blur-theory, however, one must expect that the visual acuity varies inversely with the amount of blur, and the discrepancy reported by Dr. Ogle needs further study.

The third consideration is the most important and, all by itself, can constitute the basis for the choice of a logarithmic scale. In connection with the smaller letters where ten different letters are presented for each letter size, one can think of the use of the chart as a constant stimulus technique. The percentage of the number of letters on each line which can be correctly named constitutes a specification of frequency of seeing. If these frequency-of-seeing scores for the various lines are plotted on a sheet of graph paper in which a logarithmic scale is used for letter size, and a probability scale is used for frequency of seeing (percentage), the line connecting the points turns out to be straight. When the data are analyzed in this way one obtains a true psychophysical function. One can specify the point on the letter-size scale at which the frequency of seeing is 50 per cent. even though this size falls between the sizes for the rows of letters. When one specifies a score for a given individual in terms of a letter size at which he has a 70 per cent frequency of seeing, this represents a meaningful point on the curve giving the psychophysical function.

When visual acuity is specified in terms of a logarithmic scale two individuals having different visual acuity scores will have the same standard deviation for the psychophysical function in terms of logarithmic units. This principle has also been demonstrated for a given individual made myopic to various degrees with plus lenses.

The checkerboard patterns normally used in the Ortho-Rater are graded so that there is only one checkerboard pattern for each of the checkerboard spacings. The criterion in this kind of situation is the level at which two items are missed in sequence.

Someone ought to analyze the statistics involved in this situation to relate the findings to findings based on the constant stimulus approach.

Although a logarithmic scale is used for the purpose of arriving at a specific and meaningful specification of the visual acuity, it is recognized that the visual acuity scores for different people do not indicate their relative capacities for performing a task. However, visual acuity scores have to be used for the purpose of selecting people for a given task, or for assigning people with different tasks. Consequently, it must be recognized that equal steps on a logarithmic scale of visual acuity do not represent equal steps in terms of performance of a task. However, the performance of a task is the basic underlying concept for grading the parameter for visual fitness. It may be argued, however, that if one wants the parameter of visual acuity graded into ten steps, or a greater number of steps, the steps could be uniform on a log scale, and the person who has to use the scale for selecting or assigning people will have to reinterpret the scale for his purpose. The range should extend from 20/10 to 20/400.

The question can be raised whether any suggestions can be made to help a person reinterpret a logarithmic scale of visual acuity in terms of visual fitness. One simple approach to the matter would be to use the AMA scale of visual efficiency which is designed for the purpose of meting out compensation in the case of loss of vision through accident. The general underlying concept here is that the loss in acuity will impair the capacity of the person to earn a living.

Another approach to the matter is to use the Sloan letters, or equivalent characters, in the design of a task in which performance can be studied. Consider, for example, the case of Landolt Rings. One can make up a visual acuity chart, as Dr. Sloan has done, in which Landolt Rings are used as substitutes for the Sloan letters. This is necessary in the case of illiterate people who need to be tested for visual acuity. Attention is called to a paper prepared by the writer and called "Assessment of Visual Performance," in which two different examples of tasks are described which involve the Landolt Ring, and which can be used in the study of the performance of a task.

One of these tasks is the task set up by Weston and used in the study of performance. He studied not only the effect of the size of the letter but also the contrast and the level of luminance. The subject has to scan 16 rows of 16 Landolt rings in each row and to mark the rings in which the gaps are pointing in a speci-

fied direction, which may be one out of eight possible directions. The result is scored in terms of measurements which are characteristic of performance, such as speed and accuracy. In this kind of study it is possible to relate performance to the size of the letter, and, in this way, obtain a relationship between performance and letter size.

Another type of task, described in the paper referred to above, is one in which a single Landolt ring is presented to the subject at a given time. The size, the duration of exposure, the contrast, and the luminance level can all be varied. If the interval between the presentation of one letter and the next is slow enough this kind of manipulation can be regarded as a way of measuring acuity. The thing that converts it from a measurement of acuity to a measurement of performance is the use of rates of presentation which are so rapid that the cortical processes involved in handling the information fed in through the eye become time-limited, and the only meaningful way to interpret the results is in terms of speed and accuracy. One can, of course still use Landolt rings and design a task which is infinitely more complex. Data of the type just described can be used only as a general guide in trying to relate letter size to performance.

In dealing with the problem of visual acuity, it must be recognized that each observer has two eyes, and the visual acuity in each of the two eyes may not be the same. Consequently, when rating people in terms of visual fitness it is necessary to come up with a rating which represents some kind of weighted average of the visual acuity in the two eyes.

This merely serves to indicate the complexity of the problem of specifying cutoff points for selecting and assigning personnel, and for retaining personnel. Another aspect of the problem is that in most cases the personnel involved will be permitted to wear their glasses. Hence, in such cases, the measurement of visual acuity should be made with the glasses to be worn. In some instances, where the work involves near vision, the visual acuity should be measured at the distance at which the eyes will be used, and, if a reading aid is to be prescribed, it should be used during the test. The general concept of visual fitness involves not only visual fitness at the moment, but the retention of visual fitness over a period of time, and hence things other than the visual acuity measurement itself must be taken into consideration.

It was pointed out at the meeting, for example, that if you want a man to have good distance vision without glasses at the

age of 25 when you select him at 20, the obvious thing to do is to take a hyperope who will be able to accommodate for the required distance at the age of 25. On the other hand, if you want a man to be able, without glasses, to see near-point objects at the age of 45 as well as at 35, you would have to avoid picking hyperopes who might be too presbyopic at the age of 45 to perform the task.

The problem of the presbyope is not swept away merely by saying that proper glasses will be prescribed, because a presbyope wearing bifocals (or even trifocals) is faced with handicaps by way of flexibility in his focus which would not plague a younger person. For example, he might have to have a special pair of glasses in order to pick splinters out of his fingers.

The difference between a screening test and a qualifying test should be easy to visualize, but the distinction, in some instances, is hard to make. For example, one can give a visual acuity test without glasses for the purpose of determining if the person needs to be wearing glasses. One can also test visual acuity with the old correction to determine if the glasses need changing. Measurements of this kind need not have any bearing on his ability to qualify for a given task if he can get good visual acuity with the proper pair of glasses. It is assumed that the refractive errors are measured directly, and there is no need to use visual acuity scores without glasses to assess the refractive error.

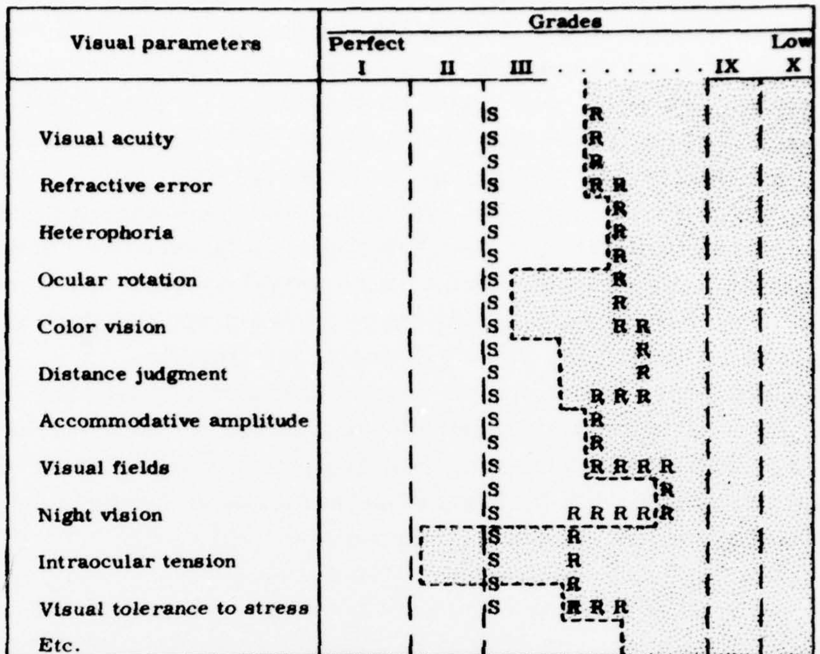
On the other hand, if a person fails to get 20/20 vision at distance with his best correction one should not immediately set out to find a job requiring low-grade vision which he can perform. An ophthalmologist or optometrist, or a team involving both, should further examine such a person to determine the cause of the reduced acuity.

An examination may indicate that he has a condition which may become worse and, therefore, he may be disqualified for a given job on the basis of the prognosis, even though his visual acuity per se would not, at the moment, disqualify him for performing the task.

After it has been determined that no active pathology is involved, and that the condition is not likely to get better or worse, then, and then only, can the person be assigned to a job for which he is qualified by virtue of his acuity measurement.

Fig. 1, in the report of Working Group 20 "Visual Requirements for Flying," implies that the different parameters should be graded in such a way that the same cut-off point should be used for each of the parameters for a given task. In the opinion of the author, the cut-off points are going to differ on different

Example of the Proposed System for Grades of Visual Fitness



Note: SSSSS selection requirements for service X
RRRRR retention requirements for job X
----- visual profile of subject Z

FIG. 1.

parameters for different tasks, not only for the purpose of retention but also for the purpose of selection.

In this connection, it may be noted that a parameter like accommodative amplitude, which is graded in terms of diopters of amplitude, will classify different individuals by age, whereas a parameter like visual acuity with the best correction is not a respecter of age. If, therefore, old people are selected for one job and young people for another, different relative weighting will have to be given to amplitude of accommodation and visual acuity in the two groups.

If one of the purposes of the testing program is to provide flexibility in which the cut-off point can be manipulated to increase the available manpower, there could be provided, ahead of time, information on how the grades for the different parameters divide the population. The author has not attempted to do this for visual acuity, although it is suspected that all the necessary data are available to accomplish this objective.

In the report of Working Group 20 it was pointed out that it is

desirable to have the cut-off point for retention flexible. This may turn out to be the hardest of all the problems. Grades of visual fitness would have no meaning if one used grade 4 for a cut-off point in Denver one day, a grade of 2 for cut-off point in Washington on the next, and then to switch back and forth. The implication in the report is that it is better to have a flexible cut-off point rather than to handle the situation by issuing waivers. It appears that the most efficient system would be to recognize that issuing waivers is a perfectly respectable precedure. The important thing is that the person who makes the decision use his best possible judgment in the interests of all concerned, and most of all, he must thoroughly understand the risk involved when a waiver is issued. It seems, therefore, that the essential problem is that people who have to make the decision about waivers be fully informed about the nature of the parameters and the risk involved in failing to take a man off a task when his scores indicate that he is not qualified.

REFERENCE

Ogle, K. N. Report on international nomenclature for designating visual acuity. Armed Forces-NRC Comm. on Vision, 1953.

VISUAL ACUITY RELATIVE TO PRESENT VISION COMMITTEE EFFORTS

Ailene Morris
Institute of Visual Sciences, Presbyterian Medical Center
San Francisco

A review of the historical developments of the efforts of the Armed Forces-NRC Committee on Vision relative to visual acuity was published in 1962 (Morris, 1962). Briefly, that review covered the areas of visual standards for acuity, phoria, and depth perception, as well as test devices and visual performance related to job success. The appointment in 1945 of the Subcommittee on Procedures and Standards for Visual Examination initiated an extensive and continuing program which has resulted in specific progress toward developing adequate and reliable tests, standardization of procedures and conditions, and the effective carrying-out of established visual screening and qualification criteria. Visual acuity wall-charts have been devised and validated, screening instruments have been developed and evaluated, and clinical testing procedures for acuity and phoria measurement have been specified. Job analyses have been carried out, visual requirements defined for job success, and visual standard selection levels recommended.

Working Group 20 in its recent report to the Committee on Vision (Jampolsky & Morris, 1962) recommended that grades of visual fitness be established for the various parameters of vision. Such grades, or grade decrements, could serve as a basis on which a flexible, dynamic system of visual standards could be constructed and appropriately adjusted to meet changing needs. This recommendation is, in fact, the reason for the current meeting on the Measurement of Visual Function.

In a supplement to the Working Group 20 report, a plan was proposed for organizing and handling the vast amount of data on vision. It was recommended that the methods and principles of

taxonomic classification be applied to human visual data. One aspect of this system involves establishing hierarchical categories, each embracing one or more lower categories. As applied to the measurement of visual functions, the sequence of categories could be based upon relative importance. The various visual functions could be arranged accordingly, and from this sequence the priority of testing order could be established. Not only should the most important visual functions be evaluated first, but the earlier tests should screen effectively and should provide maximum information, thereby conserving time in subsequent assessment, or eliminating it altogether. For example, if there is evidence of high photopic acuity and normal color vision, a good, central visual field can certainly be assumed without measuring it.

In considering the measurement of visual functions, this group would do well to take full advantage of the time, talent, and effort already invested by the Armed Forces-NRC Committee on Vision.

REFERENCES

Morris, Ailene, A review of the Armed Forces-NRC Vision Committee's activities relative to visual standards for military tasks, 1944-1954. In Milton A. Whitcomb (Ed.), Visual problems of the Armed Forces Washington: Natl. Acad. Sci. - Nat. Res. Council.

Jampolsky, A., & Morris, Ailene. Visual requirements for flying: some aspects of re-evaluation. Washington: Armed Forces-NRC Committee on Vision, Report of Working Group 20, 1964.

CLINICAL MEASUREMENT OF VISUAL ACUITY

Louise L. Sloan
Wilmer Ophthalmological Institute
The Johns Hopkins University

Clinical tests of acuity are expected to meet at least three different needs: (a) they provide qualifying tests to determine, for example, fitness for a job, eligibility for admission to a "Sight-Saving" Class, or some financial compensation; (b) they are needed in the diagnosis and follow-up of eye disease; (c) they are used in the subjective determination of errors of refraction.

Of the three types of equipment commonly employed, wall-charts, projected charts, and machine tests, the last is seldom used by the ophthalmologist because lens corrections cannot easily be varied while the patient is viewing the chart. Projected test letters are convenient but must be viewed in an otherwise dark room to prevent reduction of contrast by an unknown amount. In patients with opacities of the media, wall-charts viewed in illuminated surroundings give a more realistic measure of the degree of impaired vision. One patient with corneal scarring after an automobile accident had 20/80 vision when shown a single line on a Project-O-Chart. Using the wall chart, illuminated in accordance with Vision Committee recommendations, her vision was only 9/100.

There is agreement as to the need for standardization, or at least for specification, of such factors as contrast between test target and background, luminance of the background, type of test target, and gradation in size of target. Recent studies indicate that it may also be desirable to pay attention to the spacing between individual letters, and between the successive rows of letters.

High contrast optotypes, for example, black letters on a white background, are used for two reasons: (a) slight variations

in the reflectances of the black and white areas have no significant effect on acuity if the contrast is 85 per cent or more; (b) the test situation duplicates that of ordinary reading of black letters on a white background.

A supplementary test of the effect of lowering the contrast on acuity could be useful in selection for special tasks and might also be of value in differential diagnosis of eye diseases. Titmus Optical Company has special slides for use in their Vision Tester consisting of a series of Landolt rings of fixed size and of varying degrees of low contrast. If contrast can be adequately controlled in mass production, these slides could provide a useful supplementary test.

To the author's knowledge, ophthalmologists have never officially recommended any particular level of illumination on their test charts but accept whatever the manufacturer provides in the lighting cabinets and projected charts. If the same reasoning used in support of high contrast targets is adopted, a very high illumination could be recommended so that acuity will be unchanged with moderate deviations from the standard. A high illumination is usually considered undesirable for subjective determinations of refractive error because the associated pupil contraction reduces the size of the blur circles and makes the test insensitive. Some unpublished data of the author raises a question as to the correctness of this view. Fig. 1 shows that the well-known linear relation between decimal acuity and logarithm of illumination intensity holds also when there are uncorrected errors of refraction. These data are for the natural pupil and for an emmetropic observer with simulated, mixed astigmatisms of the amounts indicated in the graph. According to these data, there should be a greater difference in acuity with the right and with the wrong correction when the test letters are viewed in high illumination. This could mean greater sensitivity in the subjective determination of refractive error, even though the pupil is smaller. This chart, however, shows acuity in decimal units. The change in the threshold visual angle with increased blurring and the percentage of the change in acuity might show different relationships to illumination. Until it is known what units of change in letter size correspond to equally perceptible changes in legibility, one cannot decide what luminance level is best for subjective refractions. In studying eye diseases, it may be best to test several different levels. As evidence for this, figures are presented from a current study of the acuity-log I relationship in patients with various forms of eye disease.

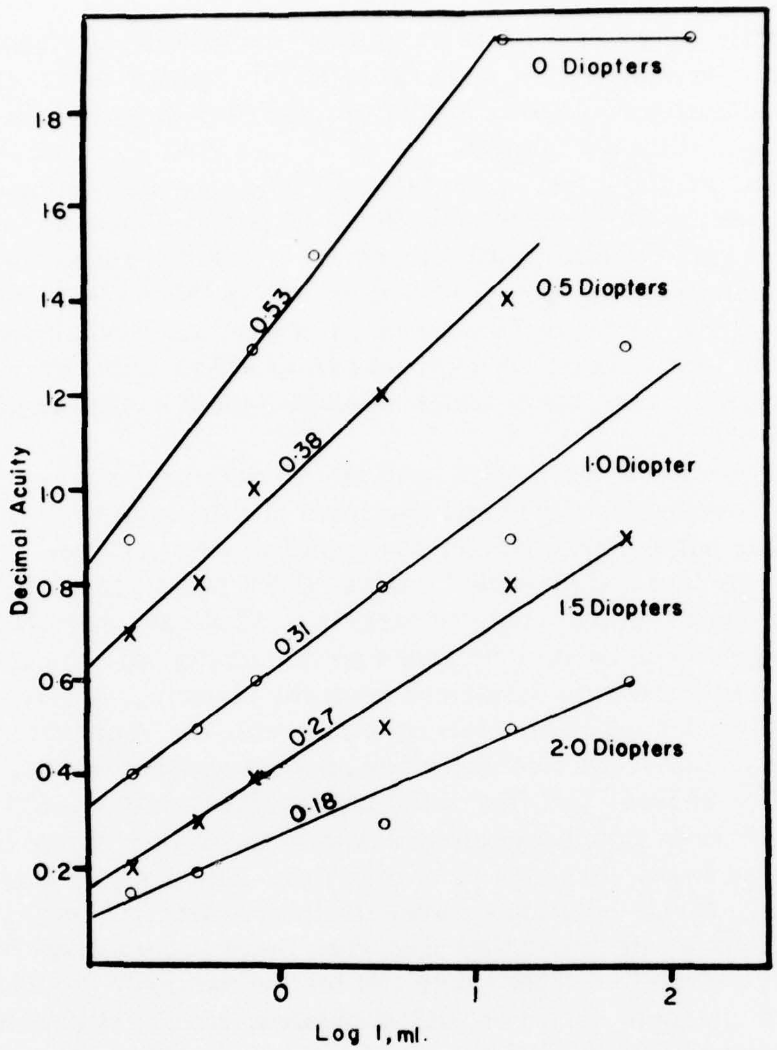


FIG. 1. Relationship between acuity and luminance in simulated errors of refraction.

These three patients with macular lesions all have a slower than normal rate of increase in acuity. This test is of practical importance in patients like Case C. His acuity is less than 20/200 at 10 ml but continues to improve with increasing luminance. At 1000 ml it is 20/50. This patient and several others whose graphs are similar read ordinary newsprint with the assistance of one of the new portable high intensity light sources. Fig. 3 illustrates a quite different form of graph in which acuity reaches its maximum at an intensity of 10 ml or less. Here, high intensity is of no benefit. It is obviously essential to specify the back-

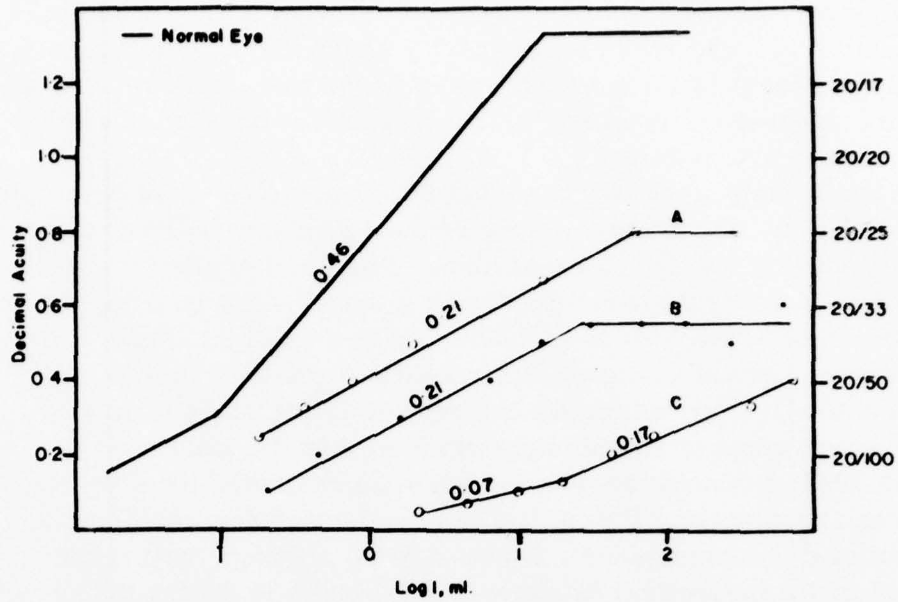


FIG. 2. Acuity-luminance relationship in three patients with macular disease.

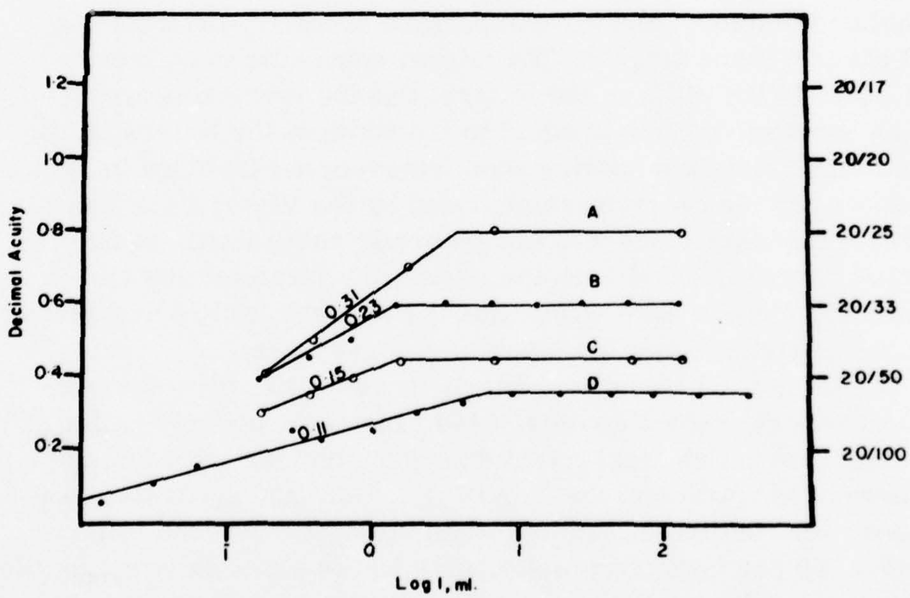


FIG. 3. Acuity-luminance relationship in four patients with optic neuropathies.

ground luminance used in any test of acuity. A possible need for different levels of testing to meet different requirements should also be kept in mind.

Another question which needs consideration is that of the best gradation of steps on a clinical acuity chart. This could be, for example, equal steps in visual angle, equal steps in decimal acuity (reciprocal of visual angle), or equal steps on a log scale (geometric progression).

Many widely-used charts do not follow any consistent principle of gradation. Exceptions are the Ortho-Rater Checkerboard Slide, which provides 15 equal steps of decimal acuity from 0.1 to 1.5, and several charts graduated in equal steps on a log scale. These include the Lancaster chart, and a Good-Lite Chart. The American Optical Company has recently duplicated the latter in a Project-O-Chart Slide. No commercially available charts with equal steps of visual angle are known to the author.

In 1953, a committee with Dr. Ogle as chairman (Drs. Byrnes, Cowan, Farnsworth, Fonda, Lancaster, Lebensohn, and Sloan as members), recommended a log gradation, although they recognized that a theoretical or experimental basis in its favor has not been clearly established.

Next under discussion is the spacing of the individual letters and lines. Fig. 4 shows the spacing used in 1950 by the author in a chart constructed for comparison of acuities at true and at simulated distance, and for comparison of letter, Landolt ring, and checkerboard targets. The lateral spaces between letters are equal to the width of the letters, and the vertical space between successive lines is equal to the width of the letters on the upper line. Standard spacing was, however, not included in specifications for the charts recommended by the Vision Committee because its importance was not generally recognized. In the Armed Forces-NRC charts and slides, the large letters are closer together to save space, and the smaller letters are spread further apart to fill up the otherwise empty areas.

The influence on acuity of nearby borders has been the subject of several recent studies. This has been variously called contour interaction, separation difficulty, and the crowding phenomenon. According to the data of Dr. Flom and his colleagues, contour interaction is maximal when the space between letters is about 40 per cent of the letter size and is practically negligible when the spacing is 3X as great, i.e. 12 per cent of the letter size. These figures are for the normal, emmetropic eye.

In subnormal vision resulting from refractive error or from eye disease, contour interaction probably extends to a wider letter separation. In squint amblyopias, acuity tested with isolated E's is often markedly better than that measured with a

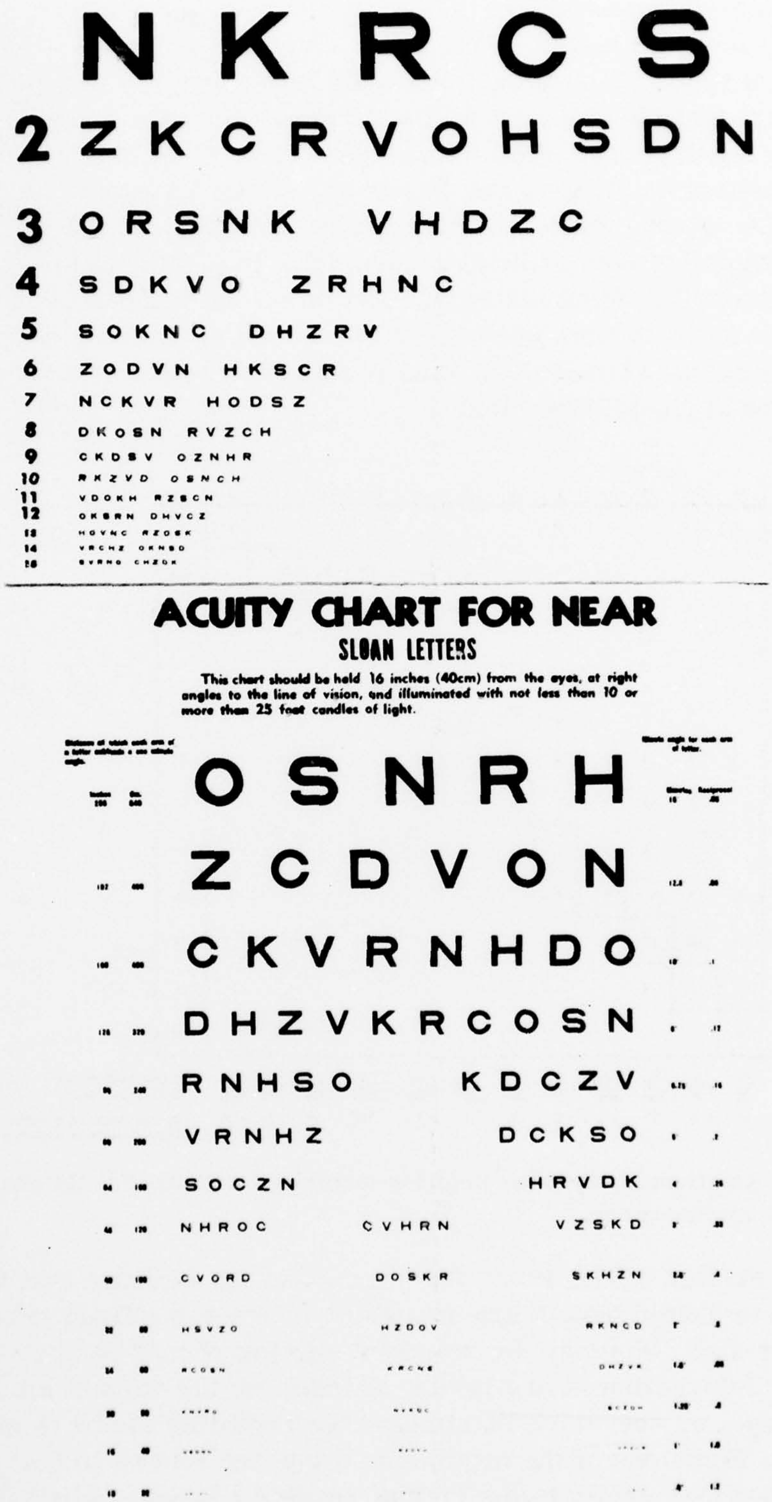


FIG. 4. Acuity chart with standardized spacing.

conventionally-spaced row of E's. In the low vision clinic of the author, acuity is tested on the letter chart shown in the previous figure in which the spacing equals the letter size. It is found, however, that the patient's ability to read continuous text is usually much poorer. This is not surprising since the spacing of the letters is close to the 40 per cent value at which, according to Dr. Flom, contour interaction is maximal. Fig. 5 shows the relation between acuities measured with capital letters and with standard reading material. The most marked discrepancies occur in patients who, because of the nature of their field defect, use a different retinal area when reading one letter at a time and when reading continuous text.

Size of Text Read With Ease at 40 cm	54	49	71	26	48	52	40	45	27	10	13	8	443
>20	1				1		1		9	5	8	8	33
20						1	1	4	2	1	2		11
14					1	1	1	4	3	1	3		14
10	1	1	3	2	1	10	8	17	9	2			54
7	1	1	2	3	4	10	13	13	4	1			52
5		1	6	5	5	15	9	6					47
4		2	12	4	14	14	6	1					53
3		3	6	6	12	1	1						29
2.5	4	4	14	5	7								34
2	10	18	20	1	3								52
1.5	13	17	8										38
1M	24	2											26
Visual Acuity for Capital Letters	20/50	20/75	20/100	16/100	13/100	20/200	16/200	11/200	8/200	6/200	4/200	<4/200	
Size of Text in M units Subtending Same Visual Angle	1M	1.5	2	2.5	3	4	5	7	10	14	20	>20	

FIG. 5. Relationship between acuities measured with capital letters and with continuous text.

The studies of Dr. Flom and his colleagues indicate that acuity charts should have a spacing which bears some fixed relation to letter size. Whether the standard spacing should be such that contour interaction is negligible, at least for the normal emmetropic eye, or one which maximizes the crowding factor is not certain. Since one of the arguments for using letters to test acuity is that they relate to the task of reading continuous text, the smaller spacing might provide the more valid measure of acuity.

There remains the final question of the best type of test target for the clinical measurement of acuity. Arguments in favor of the ten Sloan letters have been presented at length in previous Vision Committee meetings. This group of letters is used in the Armed Forces Vision Tester and wall-charts. More recently, they have been recommended by the Committee on Optics and Visual Physiology of the American Medical Association. They are available outside the Armed Services in Good-Lite Wall Charts, in an AO Project-O-Charts Slide (No. 11076), and in a special slide of the Titmus Vision Tester.

SUPPLEMENTARY REFERENCES

Flom, M. C., Heath & Takahashi, Ellen. Contour interaction and visual resolution: contralateral effect. Science, 1963, 142, No. 3594, 979-980.

Flom, M. C., Weymouth, F. W., & Kahnemann, D. Visual resolution and contour interaction. J. opt. Soc. Amer., 1963, 53, 1026-1032.

King, J. H. Discussion of the armed forces clinical acuity charts. Washington: Proc., 33rd Meeting Armed Forces-NRC Comm. on Vision, 1953. (Confidential)

Ogle, K. N. Report on international nomenclature for designation visual acuity. Washington: Armed Forces-NRC Comm. on Vision, 1953 (Jan.).

Roberts, Jean. Binocular visual acuity of adults, United States 1960-1962. Vision testing methods and binocular visual acuity findings, by age, sex and race among adults aged 18-79 years. Washington: Public Health Service, U.S. Dept. of Health, Education & Welfare, 1964, No. 1000, Series 11, No. 3.

Sloan, Louise L. Measurement of visual acuity. Arch. of Ophthal., 1951, 45, 704-725.

Sloan, Louise L. New test charts for the measurement of visual acuity at far and near distances. Amer. J. Ophthal., 1959, 48, 807-813.

Sloan, Louise L., & Brown, D. Reading cards for the selection of optical aids for the partially sighted. Amer. J. Ophthal. 1963, 55, 1187-1199.

LABORATORY APPROACH TO THE MEASUREMENT OF VISUAL ACUITY

Glenn A. Fry
School of Optometry
The Ohio State University

The laboratory approach to the problem of visual acuity is based on the need for understanding the mechanisms involved in transfer of information about fine detail in the world about us through the eyes to the brain, and the use of this information in the performance of various tasks.

The first stage of this transfer is the formation of an optical image on the retina. This is called the optical or physical factor in visual acuity.

The second stage is the conversion of the optical image on the retina to a pattern of impulses in discrete, optic nerve fibers. The predominating feature of this stage is the spacing of the photoreceptors and ganglion cells, and this is the anatomical factor.

In recent years, another factor, called retinal optics, has been identified. It has to do with the way light is collected at the retina and fed through the outer segments of the rods and cones. What it amounts to is that the number of quanta absorbed by a given photoreceptor is not related in any simple way to the average number of quanta per unit-area falling on that region of the retina. It varies with the angle of incidence.

In the retina there exists crosstalk between photoreceptors, bipolars, and ganglion cells in the form of neurological irradiation and inhibition, which constitutes the physiological factor in visual acuity. The classical way of demonstrating the role of this factor is through the study of effects of illumination level. Another physiological factor which can be separately assessed and manipulated is micronystagmus. This can either hurt or help the perception of fine detail.

At the lateral geniculate body and at the cortex, there is also crosstalk which affects visual acuity. At the cortex, one is not so much concerned about how this crosstalk impairs perception of fine detail, but rather what kind of mechanisms process the information arriving from the retina. The mechanisms involved include the interpretation, storage, and retrieval of this information.

Measurements of acuity may involve mechanisms at this level, such as attention and learning, and, to this extent, one can identify a psychological factor in visual acuity.

Visual acuity has been defined by the author as the perception of fine detail. This is deliberately vague, because in assessing the blur of the retinal image, for example, one cannot afford to be concerned with whether one is dealing with the perception of fine movements, vernier displacement, retinal disparities between the two eyes, visibility of lines and points, or the resolution of gratings. One is looking, instead, for one figure of merit which will assess the blur of the retinal image. If this figure is known then one can assess how it will affect the perception of any kind of fine detail. The same thing applies to the coarseness of the retinal, mosaic, micronystagmus, or crosstalk, between the retino-cortical pathways.

It is only when one gets to the performance of a task that one has to break the problem down into the specific kinds of fine detail that have to be perceived, and here one does not limit himself to perception of fine detail at the fovea, but to perception of fine detail at various distances from the fovea, and how eye movements, and head movements, and peripheral vision are involved in the performance of the task.

It is not important for the purpose at hand to review the numerous laboratory studies of visual acuity which have been made. However, it is important to show how one can isolate and study separately the different factors involved.

Assessment of blur. One way to specify blur is to give the spread function for a line. For the spread function one can derive a single index to specify the amount of blur. An example of this kind of index is the Fry-Cobb index, which represents the ratio of the total area under the curve to the central ordinate. Fry and Cobb used threshold measurements for a narrow bar for assessing the blur index and the spread function. Others have used the effect of blur on the contrast of a sinusoidal grating to determine the contrast-transfer function from which the spread function can be derived.

Assessment of coarseness of the retinal mosaic. At high contrast and at high levels of luminance, the coarseness of the retinal mosaic is the limiting factor in the resolution of a grating. Another approach to this problem is to view a single, bright line through a double slit which forms an interference pattern on the retina.

Retinal optics. The most striking effect related to retinal optics is the Stiles-Crawford effect, which depends on the obliquity of a beam of light at the retina. The problem can also be approached through the study of the retinal structures, and objective measurement of transmission through the retina, and the bleaching of the pigments. The distribution of these pigments in different photoreceptors also presents a problem.

Micronystagmus. By the use of various optical arrangements involving plane mirrors mounted to contact lenses, one can either measure the movements, or immobilize the image on the retina. One can also use entopic images and afterimages, which by their very nature are immobilized.

Retinal interaction. Visual acuity involves the perception of borders and gradients which make up the fine details that have to be seen, and, in this connection, visual acuity relates itself to the study of the effects of blur, and length and configuration of borders upon their visibility. It involves also the interaction of borders and the effect of luminance level.

Psychological factors. The effects of attention, motivation, and learning on visual acuity illustrate the role played by psychological factors. In reading the letters on the visual acuity chart, subjects can vary in the level at which they give up when they sense that their answers involve guessing. The effort to see may involve adjustment of the motor mechanisms controlling blur and may, therefore, indirectly improve seeing. Experience with blurred images helps the subject to develop more confidence in his hunches. The role of the cortical mechanisms which process the incoming information becomes more apparent when the subject has to process information under conditions in which the time permitted for processing is limited. It should be noted that visual scientists may be concerned, primarily, with the study of performance of tasks, and visual acuity, as such, is of secondary importance.

A scientist with this kind of approach can probably be more helpful in planning a program of acuity testing for the purpose of selecting people for a given task, or assigning people of differing capacities to different jobs.

Those who work in the laboratory also have to be concerned with the growth and development of the eye. It is also expected that data will be accumulating on visual acuity at different age levels with and without glasses. Such data must take account of sex differences and other related factors.

Furthermore, one has to be concerned with the loss of acuity from disease and trauma, and the misuse of the eyes that occurs from the cradle to the grave. Textbooks of ophthalmology are filled with specific kinds of information about the effects of disease and injury. A loss of acuity which cannot be corrected with lenses may call attention to disease or injury, but one must identify the cause in order to evaluate the ultimate, permanent losses.

Finally, it is the responsibility of the scientist to alert those responsible for testing programs about new discoveries which may point to improved methods of testing. The visual scientist should pay particular attention to objective methods which have been developed for measuring the blur of the retinal image by analyzing the quality of the image formed by light reflected from the retina and relayed by the eye to external space.

Techniques utilizing optokinetic nystagmus are already being used clinically for measuring visual acuity.

The one new possibility which has just appeared on the horizon is the use of an oscillating grating which generates an electroretinogram record which can be used in assessing visual acuity. It was reported by Dr. Riggs at a conference in Rochester in June, 1964.

The evoked potential from the occipital region of the scalp might be used in a similar way, and would give a measure of visual acuity which would represent the response of the visual system after being transmitted both through the retina and the lateral geniculate body.

REFRACTIVE ERROR
Monroe Hirsch, Chairman

CLINICAL MEASUREMENT[1]

Monroe J. Hirsch
School of Optometry
University of California at Berkeley

LABORATORY MEASUREMENT[2]

Meredith W. Morgan
School of Optometry
University of California at Berkeley

Definition (A)

Optical definitions of the three spherical-refractive states are relatively simple. Emmetropia is that condition in which rays from an infinitely distant point source come to a point focus on the retina when accommodation is suspended. Myopia exists when, under similar conditions, focus is reached in advance of the retina; hypermetropia, when the image is focused behind the retina.

Since the refractive elements of the eye usually do not comprise a perfectly spherical optical system, the rays from a distant point source of light are not brought to a point focus in most eyes. Rather, a conoid is formed having linear dimension and delineated by two foci, one for each of the major meridians of the optical system. This situation produces the fourth refractive state, astigmatism.

When the refractive state of an eye is measured, the direction and linear distance of each end of the focal conoid from the retina is determined. Operationally, however, the results are not expressed in terms of two linear distances but in terms of the dioptral power of that lens which, when combined with the optical system of the eye, will reduce the conoid to a point focus and place this upon the retina. Such a lens has two components, one which changes the conoid to a point focus (the cylindrical component), and the other which places this point upon the retina

1. Sections A, B, C, D, I, J

2. Sections E, F, G, H, K

(the spherical component). These two components, along with the axis at which the cylinder is oriented, form the customary, spectacle-lens formula.

Because the clinician deals in lens powers rather than the linear distances he is really measuring, he sometimes loses sight of just how delicate a measure refraction is. Clinically, refraction can be measured within an accuracy of 1/8 diopter (D). A 3-D lens, when added to the optical system of the eye, will move the focus one mm. Thus, changes of 1/24 mm in linear distance of the point of focus can be measured with reasonable accuracy. This is 40 microns, a pretty small increment of linear measurement for clinical testing.

Although both eyes of an individual tend to be similar, they are not precisely similar; moreover, some individuals have a difference of considerable magnitude between the refraction of the two eyes. When the difference is marked, the condition is called anisometropia. In order to describe the refractive state for one eye, two data are required; for an individual four are required, two for each eye. Refraction is expressed in terms of four measurements and in terms of the lens which will move the focal point of the system rather than in terms of the distance of the focal point from the retina.

Clinical Testing (B)

In the optical definitions, refraction is described as being measured with accommodation suspended. This simple, optical concept is not so readily put into operation in the testing situation. Accommodation may be suspended through the action of drugs on the ciliary mechanism (cycloplegia) or through physiological means, as when the subject attempts to perceive a distant object through convex lenses slightly in excess of his refractive state (fogging or cyclodamia). Each method has distinct advantages and disadvantages; each is widely used in present-day clinical practice; either yields valid results when used by a trained clinician.

The two major clinical-testing methods are the objective retinoscopic test, and the subjective technique with test-type and trial lenses. In administering either of these, the clinician not only measures refraction but also assesses the completeness of accommodative relaxation. In retinoscopy, he is sensitive to sudden changes in the reflex; he does first one eye, then the other, going back and forth several times if he is in doubt. In subjective testing, he is sensitive to qualitative aspects of the

response as well as the quantitative data being determined. He interprets his findings with the assumption that some residual accommodation always remains.

The clinician also is trained to interpret the results of several tests simultaneously. In clinical practice, visual acuity, the retinoscopic test, the subjective test and, sometimes, the keratometric test are viewed together to determine if concordance exists among the separate findings. For example, a retinoscopic finding of 1.00 of myopia for a subject with 20/20 uncorrected visual acuity immediately indicates that the subject accommodated during the retinoscopic test, cheated during the acuity test, or manifests a phenomenon new to physiological optics!

The need for clinical experience both in the administration and interpretation of refractive data presents a major stumbling block to the use of lay personnel in such testing. This will be considered again when screening by lay personnel is discussed. The two clinical techniques, retinoscopy and subjective testing, may be described briefly.

1. Retinoscopy is the most frequently used objective clinical and screening method for determining refractive state. During the test, accommodation is relaxed by chemical cycloplegia, or through having the subject direct and maintain his fixation upon a distant object. Through the aperture of the retinoscope, a hand instrument which shines a beam of light through the pupil of the subject's eye, the examiner observes the illuminated retina. As the instrument is rotated, the beam of light traverses the retina, and a shadow is observed to move; the direction in which this shadow moves tells the examiner whether myopia or hypermetropia exists. Its speed indicates the degree—the faster the motion, the less the refractive error.

The examiner, noting the speed and direction of the shadow as he rotates the instrument, introduces appropriate lenses of known power before the eye; lenses are added until a neutral (infinitely fast) motion is produced. What is happening is that light, coming from the retina as a secondary source, is being brought to a focus closer to the aperture in the retinoscope as appropriate lenses are added. The closer the focus comes to the aperture, the more rapid the motion of the reflex; when neutrality is reached the motion is infinitely fast, and the examiner recognizes this as the moment when the lens before the subject's eye is a measure of the refractive state. A correction is made for the distance between the subject's eye and the examiner's eye.

During the test, lenses may be introduced before the eye by

means of a lens bar, by individual trial lenses, or by a device with discs containing many lenses (phoroptor).

It has taken about a minute to describe this test; it takes a clinician about as long to perform it on one subject. It requires many months of practice, however, before the clinician can depend on his findings; it takes years before clini ans develop sufficient mastery of the technique to depend on the results with a high level of confidence.

2. In subjective testing, the other method of determining refractive state clinically, the same procedure of introducing various lenses of known power is used. Here, however, instead of the examiner noting the appearance of the eye as he comes closer to bringing the eye into perfect focus for a distant object, the subject is asked to report the appearance of test letters placed 20 ft from him. Systems of test charts and such psychophysical methods as bracketing are used to lead the examiner ultimately to the single lens which best fills the requirement of bringing the eye into perfect focus.

The number of subjective techniques is legion. Every clinician learns to depend on a battery of perhaps a half-dozen which he uses routinely; he knows a hundred more if these fail to elicit a response which he deems valid.

The art of subjective refraction is essentially a study in communication. The examiner communicates which form of discriminative judgment he wishes the subject to make, and aids the subject in communicating his conclusions. During the entire procedure, conditions are altered slightly, and the subject's responses are elicited. Each response suggests another comparison for the examiner to present.

Retinoscopy is a testing skill which is acquired slowly by clinicians; the performance of a subjective test is a skill which requires an even longer time to master. Only after much practice does the clinician become competent in this combination of applied psychophysics and communication. At one time or another, the examiner resorts to just about every one of the psychophysical methods.

Professionally Administered Screening Tests of Refractive State (C)

It is often desirable to determine the refractive state of a large number of persons, for instance, in a school population, or in testing for military service. Because refractive state is correlated with other tests which may be administered relatively

simply, it is not always necessary to measure refractive state per se. For example, since myopia of any appreciable degree is accompanied by a decline in vision, acuity-testing will identify those with clinically significant myopia. Astigmatism, on the other hand, is not as readily identified, and, among people under the age of 40, hypermetropia is still more difficult to identify without testing for it directly.

If a relatively accurate assessment of the refractive state is desired on a large sample of people, the retinoscopic technique is the method of choice. A trained clinician can perform retinoscopy with considerable accuracy at a rate of about one per minute. During a school day, it has been the experience of the author to find examiners doing between 250 and 300 children in five hours. The trained examiner must be assisted by a secretary to record his findings, and a monitor to facilitate the flow of subjects. The test is performed in much the same manner as in clinical practice; what modifications are introduced are to accommodate the flow of traffic; modifications are not in the basic technique nor in the concept of retinoscopy.

In performing retinoscopy, one requires in addition, of course, to a retinoscope, a fixation target, and some manner of rapidly introducing lenses before the eye. In school surveys, a continuously running, motion-picture cartoon projected on a screen 20 ft from the subject serves admirably (Hirsch, 1950). Lenses are most easily introduced by a lens bar. The steps of the lens bar can be made to fit the criteria of the particular test situation. In the Orinda study, for example, lens bars with 0.50 D steps were used. In the author's work of accumulating research data, 0.25 D steps are used so that with measuring between steps, the theoretical accuracy is 0.12 D. In addition, the subjects being tested were a pair of plus sphere spectacles to aid in physiological relaxation of the accommodation (Hirsch, 1950).

Because retinoscopy is so rapid and accurate, other screening tests are usually not used when professionals perform screening. It can be stated categorically and emphatically that there is no reason to consider screening methods other than retinoscopy unless one has no trained testers available.

An Evaluation of Professional Testing (D)

The refractive state can be determined within very close tolerances by the methods described. Good clinicians rarely differ from each other in their results on a given patient by more than 0.25 D for the refraction in any given meridian. The spectacle

lens which is ultimately prescribed for a patient is a modification of the refractive state as determined by testing; yet, even here, good clinicians differ from each other by very small amounts in the spectacle lens they would prescribe.

In regard to the specific tests, subjective testing will yield very similar results among clinicians. In retinoscopy, under screening conditions, a comparison was made by the author of the results obtained by different internes in optometry who were not aware that a comparison was being made (Hirsch, 1956). During a screening, the same child merely went through the line twice and saw a different interne each time. The refraction differed by 0.25 D, or less, 71 per cent of the time; the refraction differed between 0.26 and 0.50 D for 17 per cent of the eyes. For 12 per cent, the two tests differed by 0.51 to 0.75 D; in no instance was a difference of more than 0.75 D encountered. When it is considered that these were optometry internes who had been doing retinoscopy for less than a year, it is realized that the results for well trained clinicians would be within such remarkably close limits. It should also be noted that these tests were conducted at a rate of about 250 determinations per school day, or one per minute.

It is safe to conclude that a well trained clinician can do retinoscopy on both of a subject's eyes at a rate of about one subject per minute; if great accuracy is required, the rate might be slightly slower, but surely at least 40 subjects per hour could be tested. Under these conditions, clinicians would be expected to agree with each other (reliability of the test) within a quarter of a diopter about 75 per cent of the time, and never disagree by more than 0.50 D.

In the clinical situation, with both retinoscopy and subjective testing performed, the time required to determine the refractive state would be between 5 and 10 minutes per subject. Repeatability within limits of 0.25 D should be achieved just about 100 per cent of the time.

Because the term "refraction" is used to describe both one aspect of vision-testing and also the over-all vision test, a word of clarification is required here. A complete visual examination or "refraction" usually includes tests for pathology, a case history, tests for muscular balance, accommodation, convergence, and, possibly, other aspects of vision; it requires quite a bit of time, depending on the completeness desired. The determination of the refractive state or refractive error which is being discussed here can be achieved in less than five minutes clinically

or about a minute in screening situations. This is one part of a total "refraction."

Laboratory Testing (E)

The clinical determination of refractive error involves not only the measurement of the error but also the determination of a lens correction that will be acceptable to the patient and which will promote efficient and comfortable use of the eyes. Thus, the aim of the clinical measurement is not just to measure the error of refraction, but it is also concerned with its correction. Proof that the error has been measured and corrected properly is determined by such factors as improved visual performance, report of increased comfort, and, most importantly, by patient satisfaction. Clinicians believe with Cervantes that, "The proof of the pudding is in the eating."

Over the years, clinicians have developed techniques for the subjective determination of ametropia which will result in satisfactory corrections. These techniques are modified psychophysical measurements with built-in biases, such as the concept that the spherical error is represented by the strongest convex sphere which creates maximum acuity, or the concept that the astigmatism is represented by the weakest cylinder which creates maximum acuity. In essence, the aim of clinical refraction is not the determination of the error of refraction but its correction.

From the laboratory point of view, however, the aim is to determine the error of refraction with little regard to patient acceptance of the correction. In order to measure the degree of ametropia, a large number of optometers have been developed. In general, these optometers are either subjective or objective. Subjective optometers require the patient to make a judgment or to report what he sees. Objective optometers merely require the patient to maintain fixation.

The most fundamental subjective optometer is that of Scheiner. This consists primarily of a diaphragm containing two small apertures centered before the pupil (Fig. 1). If the retina is conjugate to a distant light source, the subject is emmetropic and reports that he sees only one light. On the other hand, if the subject has a refractive error, he will report that he sees two lights. The measurement of the error is accomplished by placing a lens before the diaphragm which will make the retina conjugate to the distant source.

The Scheiner principle has been incorporated in other optometers, such as that of Young and that of Fry. Young's optometer

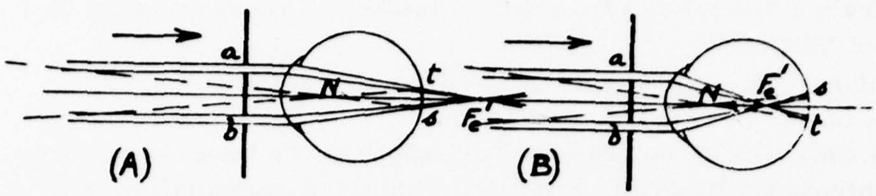


FIG. 1.*

is illustrated in Fig. 2. Here, the diaphragm before the eye contains two vertical slits, separated by about 1-1/2 mm. In front of this diaphragm is located a convex lens of about +10.0 D. Then a thin pin or line object placed 10 cm before this lens would be represented on the retina of an emmetropic eye as a single image. If the eye were myopic, the pin would need to be brought nearer the lens; if the eye were hypermetropic, it would need to be pushed away from the lens. The degree of ametropia in the meridian, at right angles to the slits, can be determined by the position at which the pin is seen as a single object.

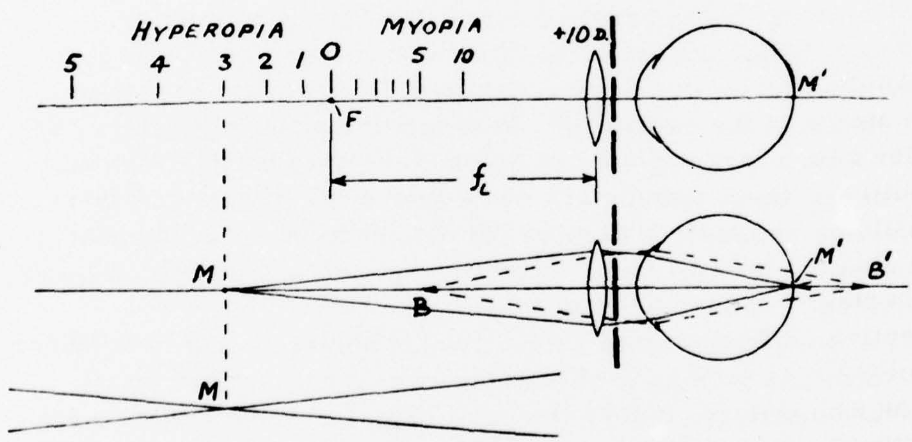


FIG. 2.

*Figures 1-8 in this paper reproduced from H. H. Emsley, Visual optics, 1952, Hatton Press, London, with permission of the publisher.

Fry's optometer (Fry, 1937; 1945) is essentially a modification of Young's. In this case, however, the slits are created in the plane of the pupil by optical rather than by physical means. Also, one slit is placed eccentrically in the upper half of the pupil while the other is in the lower half, either centrally or eccentrically. Thus, the optometer object is conjugate to the retina when the subject reports a coincidence of the two streaks of light. This optometer, using the aligning power of the eye, is more sensitive than those depending on resolution.

Other optometers have been designed using stigmatoscopy in which the point conjugate to the retina is determined by using a small point source of light and a Badal optometer. Here, conjugacy is determined when the image has its smallest diameter or the light appears brightest.

Still others have used the chromatic aberration of the eye. This principle is shown in Fig. 3.

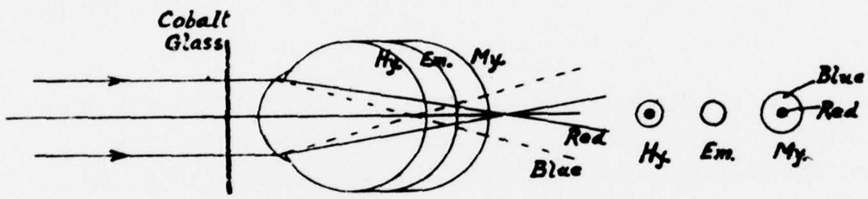


FIG. 3.

Another type of subjective optometer is based on visibility. The assumption is made that objects which are conjugate to the retina can be seen under lower contrast and lower luminance conditions than objects which are not in sharp focus. Such a sensitometric optometer has been designed and used by Luckeish and Moss (1943).

In addition to the various subjective optometers, a number of objective optometers have been designed and used. Some of these employ the principle of the ophthalmoscope, in which an image of the subject's fundus is observed through a viewing telescope. In others, an image is created on the subject's fundus. In either case, the focus required to see the fundus sharply, or the image on the fundus sharply, can be determined, and this gives a direct measure of the refractive error. The two best-known instruments of this type are the Zeiss Parallax Refractionometer and the Rodenstock Refractionometer. The optical system of the Zeiss instrument is shown in Fig. 4.

The Fincham Coincidence Optometer is somewhat similar to

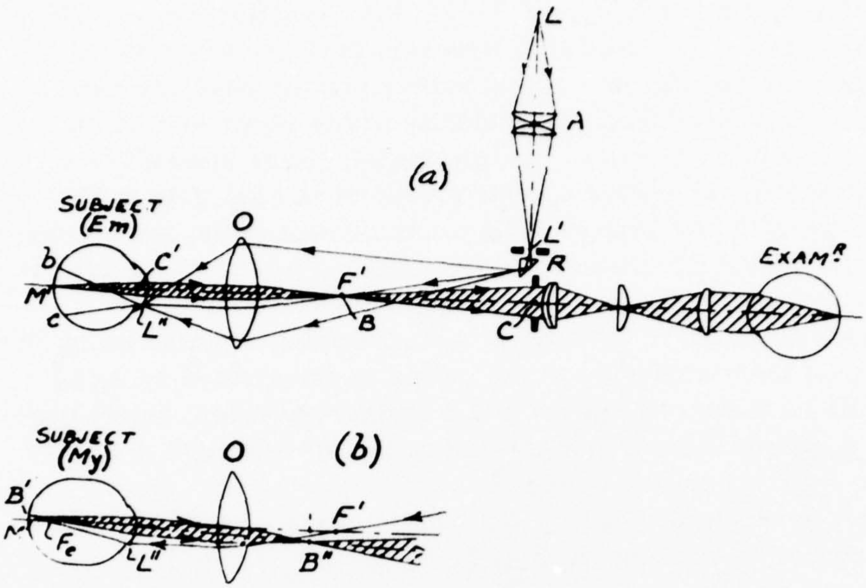


FIG. 4.

the Zeiss and the Rodenstock instruments, except that the principle of coincidence, rather than sharpness, is used to tell whether the instrument is in focus. Here, an image of a fine-line target is formed on the subject's retina which is viewed by an examiner through a telescope with an optical doubling and displacing system, so that the resulting two half-lines are out of alignment and blurred if the object is not conjugate to the retina. The adjustment of the dioptric stimulus value of the fine-line target to obtain sharpness and alignment of the two half-lines gives a measure of the ametropia. The optical system of the Fincham instrument is shown in Fig. 5.

Collins (1937), Campbell (1956), Allen (1960; 1961; 1962) and others have all described electronic optometers. In general, electronic optometers detect either the intensity or the movement, or both, of aerial images or retinal images by means of photomultiplier tubes. These devices operate very rapidly, and successfully detect small, rapid fluctuations in accommodation. So far they have not been used successfully to measure states of refraction.

In 1962, Howland and Howland (1962) reported on a photographic objective optometer. As far is known, this device has not been used to measure the refractive error of human observers.

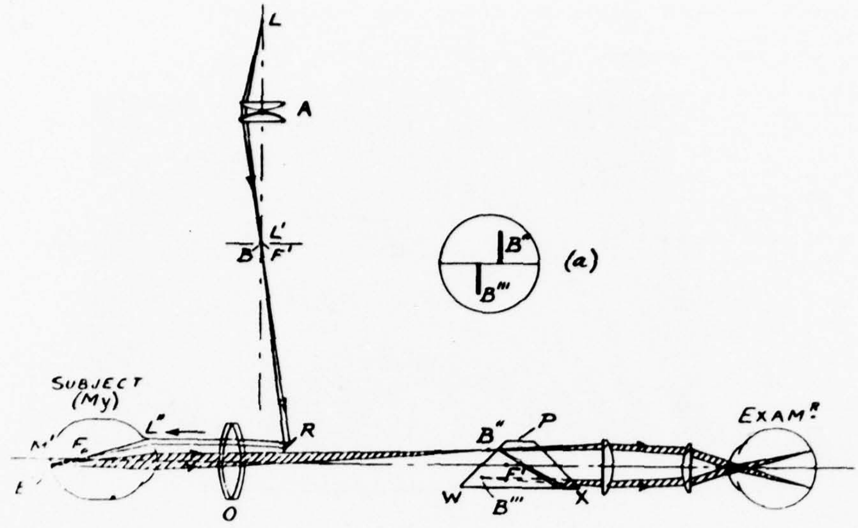


FIG. 5.

Lay Testing (F)

Obviously, there is a relationship between uncorrected errors of refraction and visual acuity, particularly in regard to myopia and myopic astigmatism. From time to time, it has been proposed that this measurement of visual acuity is all that is needed to reveal significant errors of refraction. If this should be true, individuals could be screened for the presence or absence of significant errors by the simple process of determining the acuity in each eye. Such tests could be performed by trained laymen or nurses.

In 1961, Peters (1961) reported on a study of the relationship of visual acuity and refractive error for individuals in the age groups of 5-15, 25-35, and 45-55. The results are shown in Figs. 6, 7, and 8. It will be noted that Peters avoided the use of equivalent sphere by reporting the data with cylinder power plotted as the ordinate and spherical power as the abscissa. The smooth curves are lines of iso-oxyopia-equal visual acuity. The curves do not, however, indicate whether with-the-rule or against-the-rule astigmatism is more significant.

It is apparent from these graphs that visual acuity decreases in a uniform manner with increasing myopia at all age levels. The change with hypermetropia differs, particularly in the older group. While it is possible to use these graphs to predict probable visual acuity if the refractive error is known, it is obvious that it is not possible to estimate the type and degree of the error if the visual acuity is known.

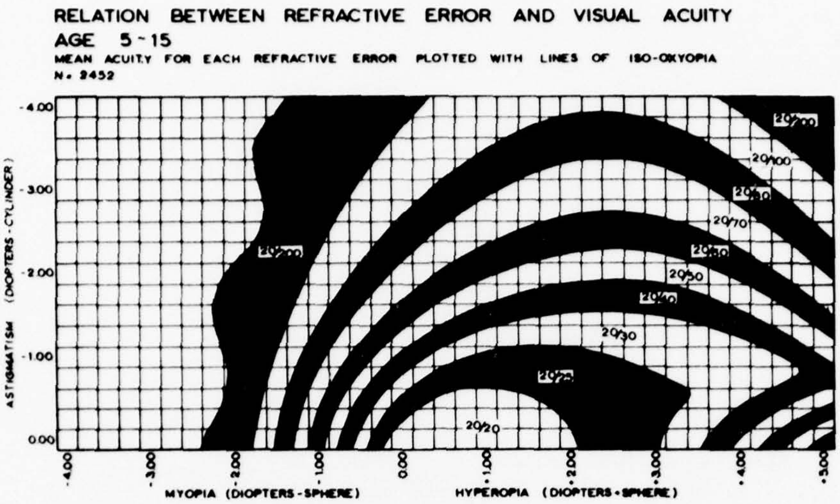


FIG. 6.

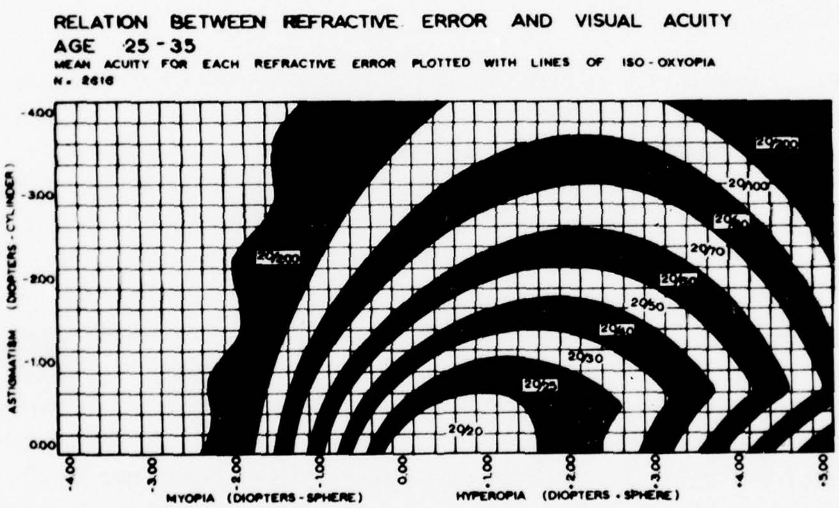


FIG. 7.

The Eames Eye Test (World Book Co., 1938) and the Massachusetts Vision Test (Welch-Allen, Inc., 1950), which are designed as vision screening tests to be performed by laymen, attempt to measure the degree of hypermetropia, within limits, by the utilization of a plus sphere test. Stewart (1950; 1956) has evaluated this technique and found that there was a poor correlation between the test results and normal clinical refractive procedures.

Other more complex devices, usually stereoscopes, such as

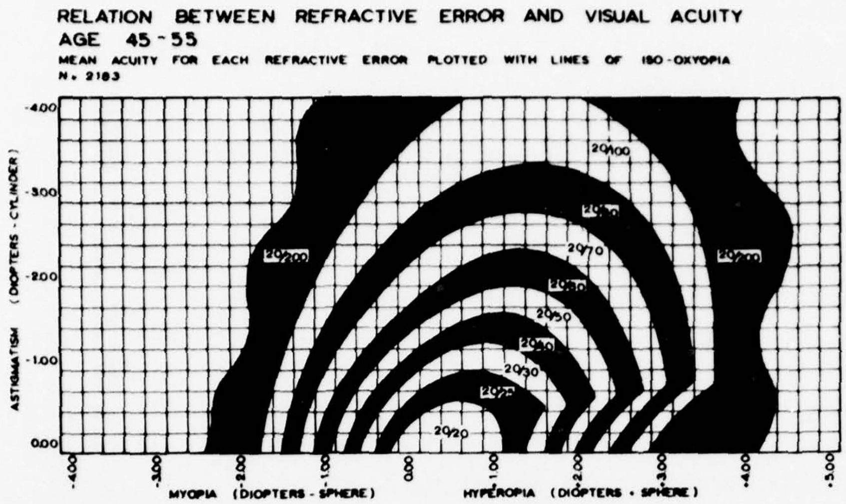


FIG. 8.

the Telebinocular, the Ortho-Rater, and the Sight-Screener, have been designed for visual screening by laymen. Since the ability of these instruments to detect the type and degree of ametropia is largely a function of the measurement of visual acuity, it would appear that these devices offer little hope for the satisfactory measurement of refractive error (Blum, Peters, & Bettman, 1959).

Evaluation of Laboratory and Screening Techniques (G)

Before methods of evaluation can be discussed, it is necessary to establish some standard to which these various techniques can be compared. As has already been mentioned, clinicians tend to use the standard of patient reaction. If there is any single criterion that clinicians tend to trust the most, particularly when applied to adults, it is the measurement of the refractive error by subjective techniques. If this criterion is applied to the results of subjective optometers, it will generally be found that these optometers give results which indicate that the ametropia measured is more myopic than that determined by clinical subjective refraction (Fry, 1937; Luckeish & Moss, 1943; Morgan, 1944; Nadell, 1956).

The objective optometers, such as the Rodenstock and the Fincham, are used by some clinicians, particularly in Europe, instead of retinoscopy. The fact that these same clinicians still do a subjective refraction before prescribing lenses indicates that these instruments, even in the hands of experienced clini-

cians, are not precise enough for dependable refraction, if precise means a prescription that a subject finds acceptable in terms of performance and comfort.

The reasons for differences between clinical subjective determinations of ametropia and the optometer determinations are not precisely known. First of all, clinical subjective refraction has a plus bias since the most convex lens power, giving maximum acuity, is generally accepted as the proper lens. Second, this lens is determined by noting the subject's responses to an altered stimulus situation. In other words, the measuring lens also affects the stimulus pattern. Third, many optometers do not utilize the whole of the pupillary aperture. Thus, the error measured by these devices is not the mean error for the whole aperture, but an error measured, using only a portion of the aperture. Fourth, clinical refraction utilizes complex targets such as Snellen letters, and, hence, perceptual responses are utilized as will be true when a lens correction is worn. Such is not the case in optometers. In most optometers accommodation is difficult to control because of the proximity of the testing target.

This difference between clinical subjective refraction and refraction by optometers is usually not great. There are times, however, when this difference is great, and unfortunately, these times cannot be predicted or identified in advance. Optometers, particularly the electronic ones, are useful not so much as devices for determining ametropia but as instruments for the automatic, rapid recording of changes in accommodation. In a sense, they are useful in the determination of relative and not absolute refraction.

Distribution of Refractive Errors (H)

A good deal is known about the distribution of refractive errors in non-selected samples of school children between the ages of 6 and 15. Unfortunately, not very much is known about the distribution below age 6 or after age 15, for non-clinical samples. The Orinda Study (Blum et al., 1959) found in the youngest group tested, ages 5, 6, 7, that 18 per cent had a "vision problem" (not all "vision problems" were refractive), and in the oldest group tested, ages 13, 14, and 15, that 31 per cent had a "vision problem." Most of this increase was due to an increase in myopia. In 1958, Morgan (1958) reported on the refractive errors of a small group (N = 95) of 34-year olds, selected on a non-visual criterion. Of these, approximately 45 per cent of the females

had a refractive error that was corrected, or needed correction, whole only 25 per cent of the males needed lenses, or just about 37 per cent of the group as a whole had refractive errors needing correction. In contrast to the change in the school children, the increase in the need for correction in this older group was largely due to hypermetropia and astigmatism. This need for correction was not necessarily due to changes in the degree of ametropia but was due in part to the decrease in accommodative amplitude with age.

As the age of the population studied becomes older, the differences between a general, non-selected sample and a clinical sample become less and less and probably have no significance when the population age reaches 55. On the basis of clinical samples, it is known that the percentage of the population with correctable hypermetropia and against-the-rule astigmatism increases more than the percentage of other errors and that by the age of 60, about 40 per cent of the population has refractive errors, not including presbyopia, which need correction (Hirsch, 1958). If presbyopia is included, nearly 100 per cent of the population suffers from an anomaly of ocular focus by the age of 50.

The Difficulty in Setting Refractive State Standards (I)

In the report of Working Group 20 presented to the Armed Forces-NRC Committee on Vision, Drs. Jampolsky and Morris and the co-committee members suggested that the various visual attributes be evaluated on a scale of visual fitness ranging from grade I to X (Jampolsky & Morris, 1964). But while such attributes as visual acuity or accommodative amplitude may be described by a single numerical value, refraction is usually described by several numbers. In order to place refraction on a simple scale, it would be desirable to reduce refractive data to a single value.

In describing an individual's refractive state, one deals with the following values:

1. spherical error for each eye
   a. nearsightedness, or myopia
   b. farsightedness, or hypermetropia
2. astigmatism for each eye
   a. With-the-rule, or direct astigmatism
   b. Against-the-rule, or inverse astigmatism
3. difference between the two eyes, or anisometropia.

In order to set refractive error on a scale, each of the attributes must be evaluated. A perfect refractive state is easily identified on an optical basis. Grade I would include those sub-

jects who had no spherical error and no astigmatic error in either eye. However, such visual systems are almost non-existent in the human population. Grade I must also include some degree of error. But how much astigmatism is an equivalent error to how much spherical error? How much hypermetropia is equally undesirable to how much anisometropia?

There are no simple answers to these and similar questions. Were visual acuity the sole criterion, the problem would be relatively simple. The effect on acuity of refractive error has been studied by many investigators; most recently, Peters (1961) has presented a graph for predicting distance acuity from refraction. But distance acuity is not the only consideration. The effect of certain refractive errors on near acuity is different from the effect on distance acuity. The effect of refractive error on binocular achievement is a further complication.

As a first approach to the problem, a system has been devised by the authors for reducing the data of an individual's refractive state to a simpler form.

A Suggested Plan for Scaling Refractive Data (J)

On a grid marked off in quarter-diopter steps, the refractive state of an eye can be plotted. The abscissa represents power in the horizontal meridian; the refractive error in the vertical meridian is represented by the ordinates. Such a grid is shown in Fig. 9. On this grid, one can identify the various refractive conditions.

The point X is zero in each meridian and, hence, is emmetropia. The squares filled in along the 45-degree (°) slope represent the spherical refractive state; those that are cross-hatched are spherical hypermetropia; those that are darker are spherical myopia. Square Y represents a refraction of +2.25 Diopters of sphere (D.S.), and square Z a refraction of -2.00 D.S. Any point above the line represents against-the-rule astigmatism; below the line is with-the-rule astigmatism. The further the point is from the 45° slope, the more the astigmatism. Thus, all points marked No. 1 have 0.25 D of against-the-rule astigmatism; all points marked No. 2 represent 0.50 D of inverse astigmatism; No. 3 is 0.75 D, No. 4 is 1.00 D, etc. Similarly, squares marked with primed numbers have with-the-rule astigmatism of appropriate amounts. Squares No. 1' represent 0.25 D, squares No. 2' represent 0.50 D, etc.

On such a grid, the refraction of two eyes can be plotted. Squares A and B are placed, for example, to represent two eyes.

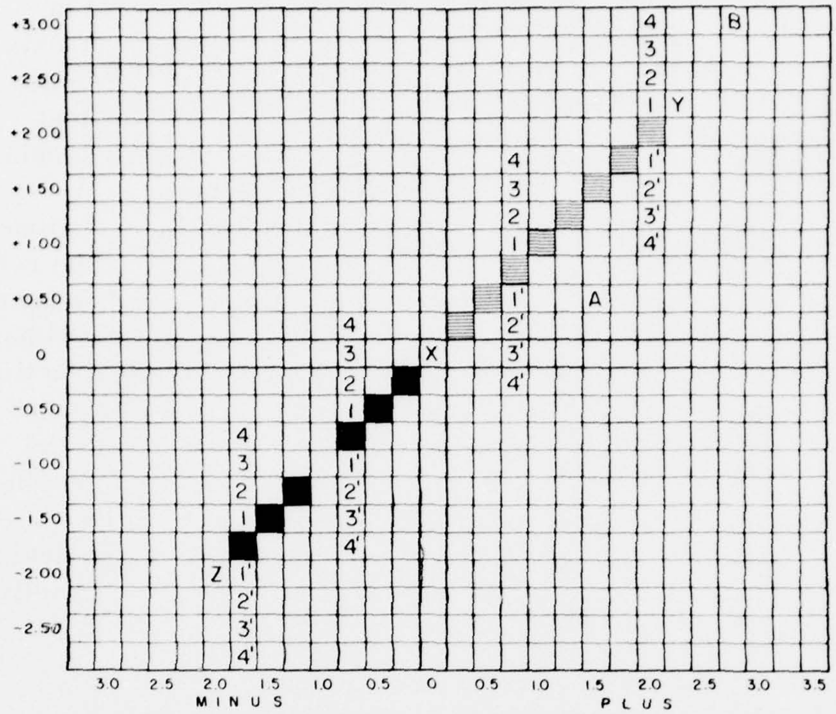


FIG. 9.

Square A would be an eye which had refraction of +1.50 in the horizontal meridian, and +0.50 D in the vertical. The spectacle lens correcting such refraction would be

$$+\ 1.50 = -1.00 \times 180, \text{ or}$$
$$+\ 0.50 = +1.00 \times 90.$$

Point B, representing the other eye, has a refraction of +2.75 D in the horizontal meridian, and +3.00 D in the vertical. Its spectacle formula, of course, is

$$+\ 3.00 = -0.25 \times 90, \text{ or}$$
$$+\ 2.75 = +0.25 \times 180.$$

On such a graph, isoptors could be drawn which represent the various grades. The basis for drawing the isoptors would have to be determined by a group of experts in refraction. These experts would have to agree upon the degree of hypermetropia, astigmatism, and anisometropia which would be allowed in each grade. If hypermetropia were deemed to be less of a handicap than myopia (as it is in the lower grades at least), the isopter would encompass more area to the right than to the left of the origin. If against-the-rule astigmatism is more serious than

with-the-rule astigmatism, then the isoptors would encompass more area below the 45 ° slope line.

A set of theoretical criteria were accepted here, for example, to illustrate the use of such a graph. It is stressed that the ultimately accepted criteria, however, would require the pooled experience of a group who work with refraction.

TABLE 1. Theoretical Criteria for Isoptors

Grade	Myopia	Hypermetropia	WR Astig.	AR Astig.
I	none	0.75	0.25	0.25
II	0.25	1.25	0.50	0.50
III	0.75	1.75	1.00	0.75
IV	1.25	2.25	1.50	1.00
V	1.75	2.75	2.00	1.25
VI	3.00	3.50	2.50	1.50

The isoptors corresponding to these criteria are shown in Fig. 10. For a single eye, the graph has no value over a simple table of criteria. However, there are advantages, when an attempt is made to incorporate the data for the two eyes into a single value or grade of visual fitness.

It has been noted that if each eye is plotted graphically, the distance between the two points is a measure of the anisometropia. For simplicity, this distance may be expressed in terms of the number of moves it would take a king on a chess-board to reach one point from the other. The king, it will be recalled, can move one square in any direction. Referring to Fig. 10, it is noted that to go from A to B, the minimum number of moves is 10. To go from Y to B takes 3 moves. To go from X to Y takes 9 steps. To go from A to Y takes 7 steps, etc.

In expressing the refractive state for an individual, therefore, the data have been reduced to three values; the grade for the right eye, the grade for the left eye, and the number of steps separating them. A simple formula could be used to reduce these three to a single grade. Inherent in it would be an evaluation of the degree of difficulty anisometropia might be expected to bring about. An example of such a formula (not necessarily the one which should be used) is presented here:

Let A = the grade for the right eye
Let B = the grade for the left eye
Let X = the number of squares between the two.

$$\text{Grade} = \frac{A + B}{2} + \frac{X}{3}$$

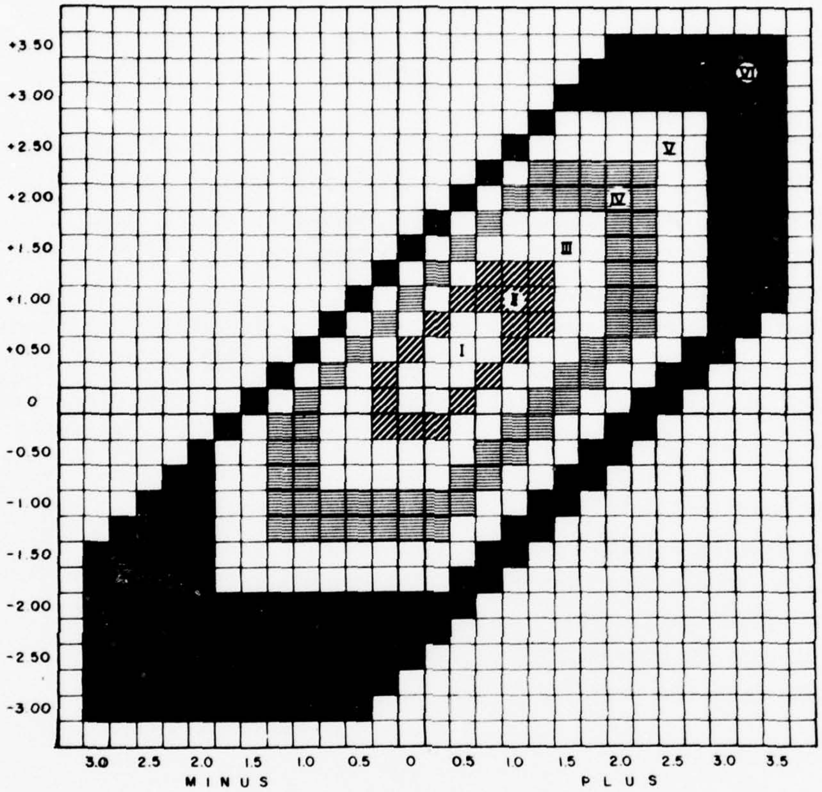


FIG. 10.

A few examples will suffice to demonstrate this simple relationship.

Example 1

Right eye	+ 0.75	$\frac{1 + 1}{2} + \frac{0}{3}$	= 1 = Grade
Left eye	+ 0.75		

Example 2

Right eye	0.00	$\frac{1 + 1}{2} + \frac{3}{3}$	= 2 = Grade
Left eye	+ 0.75		

Comparing these two examples, it is seen that the second pair of eyes, although each eye is Grade 1, will get a score of Grade 2 because of the 0.75 D of anisometropia.

In this formula, what is being done is averaging the grade of the two eyes, and adding a factor to express degree of anisometropia. But a final formula need not follow this. The denominator of the anisometropia fraction can be any number selected. If the denominator of the second expression is two, more emphasis is being placed on anisometropia; if four is selected, less emphasis is being placed on anisometropia. The formula, needless to say, is only as valid a measure of visual fitness as the judgments which go into its construction.

Also, the denominator of the first expression was selected as two. However, this could just as easily be one or three. This would depend on a judgment of how important the second eye is. Insofar as distance acuity is concerned, the poorer eye of a pair contributes little.

What has been presented is a method of reducing the complex data for refraction of a pair of eyes to a simple grade of visual fitness. It is suggested that if visual fitness is to be placed on a scale, a group of experts in refraction determine the exact location of the isoptors and the exact nature of the equation. Once these are established, a clerk could be trained to grade refractive data quite rapidly. The validity of the grades assigned, however, will always be no better than the data which go into establishing the isoptors and formula. These serve only to simplify complex, interacting variables into a single value; they do not increase the validity of the basic assumptions.

Conclusions (K)

Refractive errors may be measured by clinical and laboratory techniques. The best laboratory techniques which can be used by laymen involve the use of objective optometers. Such techniques, however, cannot be used to indicate the absolute need for nor the prescription for a correction. Refraction cannot be isolated from a consideration of visual needs, the amplitude of accommodation, and the state of binocular vision. There can be no positive substitute for clinical judgment.

REFERENCES

Allen, M. J. A study concerning the accommodation and convergence relationship. Wright-Patterson AFB: Aeronautical System Div. tech. Rep., 1961, No. 61-111.

Allen, M. J. Calibration of the infra-red optometer. Wright-Patterson AFB: Life Support Systems Lab. tech. doc. Rep., 1962, No. 62-88.

Allen, M. J., & Carter, J. H. An infra-red optometer to study the accommodative mechanism. Amer. J. Optom. & Arch. Amer. Acad. Optom., 1960, 37, 403-407.

Blum, H. L., Peters, H. B., & Bettman, J. W., The Orinda study. Berkeley: Univer. Calif. Press, 1959.

Campbell, F. W. J. Physiol., 1956, 133, 318.

Collins, G. Brit. J. phyiol. Opt., 1937, 3-40.

Emsley, H. H. Visual Optics, Vol. 1. London: Hatton Press Ltd., 1952.

Fry, G. A. An experimental analysis of the accommodative-convergence relationship. Amer. J. Optom., 1937, 14, 402-414.

Fry, G. A. The relation of the pupil size to accommodation and convergence. Amer. J. Optom. & Arch. Amer. Acad. Optom., 1945, 22, 451-465.

Hirsch, M. J. A skiascopic procedure for visual screening surveys. Amer. J. Optom. & Arch. Amer. Acad. Optom., 1950, 27, 12, 587-591.

Hirsch, M. J. The variability of retinoscopic measurements when applied to large groups of children under visual screening conditions. Amer. J. Optom. & Arch. Amer. Acad. Optom., 1956, 33, 8, 410-416.

Hirsch, M. J. Changes in refractive state after the age of forty-five. Amer. J. Optom. & Arch. Amer. Acad. Optom., 1958, 35, 229-237.

Howland, B., & Howland, H. C. Photographic method for the study of vision from a distance. MIT: Res. Lab. of Electronics, 1962, Quart. Progress Rep., No. 67, 197-204.

Jampolsky, A. & Morris, Ailene. Visual requirements for flying: some aspects of re-evaluation. Washington: Report of Working Group 20, Armed Forces-NRC Comm. on Vision, 1964.

Luckeish, M. & Moss, F. Comparison of a new sensitometric method with the usual technics of refraction. Arch. Ophth., 1943, 30, 489.

Morgan, M. W. Accommodation and its relationship to convergence. Amer. J. Optom. & Arch. Amer. Acad. Optom., 1944, 21, 183-195.

Morgan, M. W. Changes in refraction over a period of twenty years in a nonvisually selected sample. Amer. J. Optom. & Arch. Amer. Acad. Optom., 1958, 35, 281-299.

Nadell, M. A. The effect of various luminance levels and target configuration on the refractive state of the eye. Wright-Patterson AFB: Wright Air Develop. Cntr. tech. Rep., 1956, No. 56-61.

Peters, H. B. The relationship between refractive error and visual acuity at three age levels, Amer. J. Optom. & Arch. Amer. Acad. Optom., 1961, 38, 194-199.

Stewart, C. R. Plus-lens visual acuity screening test. Optom. Weekly, 1950, 41, 615-618.

Stewart, C. R. Investigation of plus-lens visual acuity screening test. Optom. Weekly, 1951, 42, 9-13.

Welch-Allyn Ins. Massachusetts Vision Test. Auburn, N. Y., n.d.

World Book Co. Eames Eye Test. Yonkers-on-Hudson, N. Y., 1938.

COLOR VISION

Robert Boynton, Chairman

PRECEDING PAGE NOT FILMED
BLANK

THE MUNSELL COLOR-CIRCLE AND THE FARNSWORTH-MUNSELL 100-HUE TEST

Arthur Linksz
School of Medicine
New York University

The Farnsworth-Munsell 100-Hue Test consists of a selection of movable, colored paper chips. Together and in proper order, these chips form a Munsell color circle. As is well known, a full Munsell circle consists of 100 hues. For the purposes of this test, the number has been reduced to 85 samples, since some samples were found to be redundant and were dropped. Fig. 1 demonstrates the loci of these 85 color chips in the I.C.I.

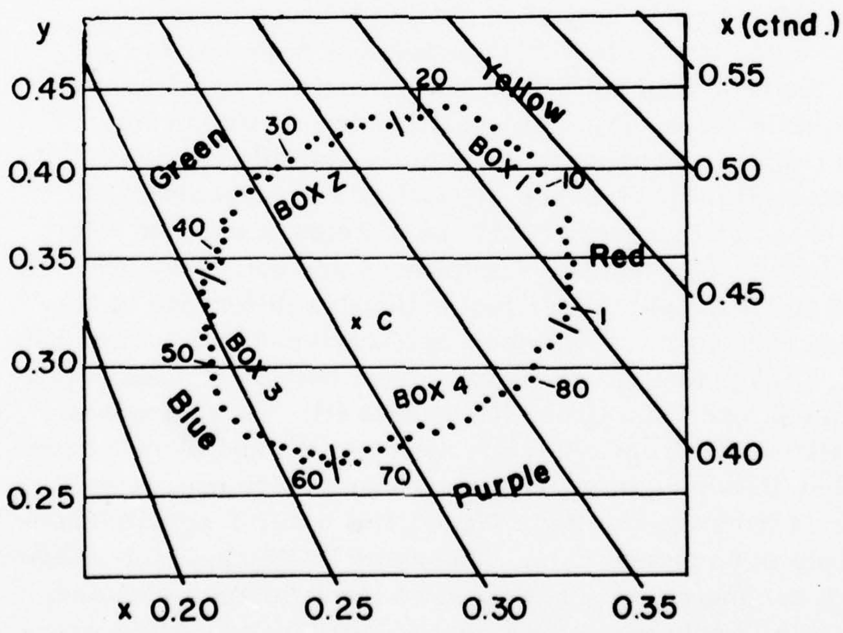


FIG. 1. Locus of 85 hues of Farnsworth selection in chromaticity diagram.

chromaticity diagram, arranged in a circle around "C," the locus of standard white (or gray). The distribution is quite even and the distance of the individual samples from "C" quite uniform. All of the samples are rather desaturated, and they are more or less equal in brilliance. It is the hue, not the chroma, not the value, for which the chips are to be compared and by which they are to be differentiated.

One cannot help suspecting a certain artificiality in a color circle which consists of 100 hues. One will suspect that such a round number is a predetermined number. Quite likely, Munsell dropped some samples or, even more likely, added some for the sake of the roundness of the figure. This has been rather well corrected in the Farnsworth selection. The Farnsworth selection comes closer to Munsell's ideal than Munsell's own: the 85 samples do differ from each other by a "just noticeable difference in hue," while among the original 100 samples some are hardly distinguishable. A certain added artificiality, the interference of a predetermined scheme, manifests itself in the allocation of color names, and in the distancing of the primal hues. The 100 hues of the Munsell circle are divided into five equal compartments—a division which has no physiological basis whatever. However esthetically attractive Munsell's five-pointed star arrangement is to the eye (Fig. 2), there can be only four primal loci in a color circle—any color circle—because there exist only four color modalities, and the distance from one primal color to the next need not necessarily contain an equal number of discernible steps. True, an equal number of steps exists between neighboring primal colors in the Ostwald circle of colors also (Fig. 3). However, the Ostwald arrangement is frankly based on theory (Ostwald had a theory about how colors should blend), while Munsell's sequences are not. They are based on the principle of the "just noticeable difference in hue." One must, therefore, expect some arbitrariness in selection if—in spite of the principle—steps each from Red (R) to Yellow (Y) to Green (G), and from Green (G) to Blue (B). There are also twenty steps each from Blue (B) to Purple (P), and from Purple (P) to Red (R) which, of course, means that there are, in fact, forty steps from Blue to Red. The capital letter P notwithstanding, purple is no primal color. The name is attached, for reasons of design symmetry, to some balanced blend between blue and red. Purple is only one of the great number of hues which are blends of blue and red.

Farnsworth's selection of 85 samples (Fig. 4), even if a more

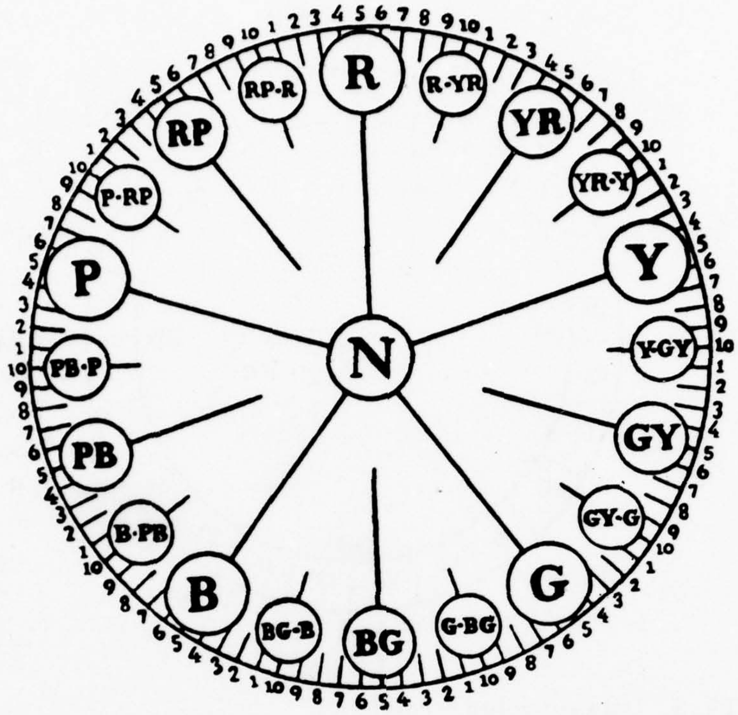


FIG. 2. Munsell color circle.

realistic selection, perpetrates some of these questionable features of Munsell's. The number of blended hues between R and Y, between Y and G, and between G and B is constant once made, and the number of blended hues between B and R is again twice this number. To be sure, the number of discernible blended hues between primal blue and primal red is, in fact, larger than the number of discernible hues between any other two primal colors, say, green and blue. In this respect, Munsell came closer to sensory reality than Hering or Ostwald. Munsell's designation of the blend between blue and red with a single letter, "P," has also been retained by Farnsworth. Retention of these poorer features of the Munsell arrangement, and especially the artificiality of the symmetric pentagonal arrangement, led to such obvious inconsistencies as the assignment of the notation "R" (for primal, sensorially pure Red) to chip #1, the dominant wave length of which is given as ca. 610 mμ. Farnsworth's "R" is obviously a yellowish red and so is, of course, any spectral red. The notation "YR" (for balanced orange) is, again for symmetry, assigned to chip # 10, the dominant wavelength of which is given as ca. 585 mμ. To normals, the hue of this wavelength is a yel-

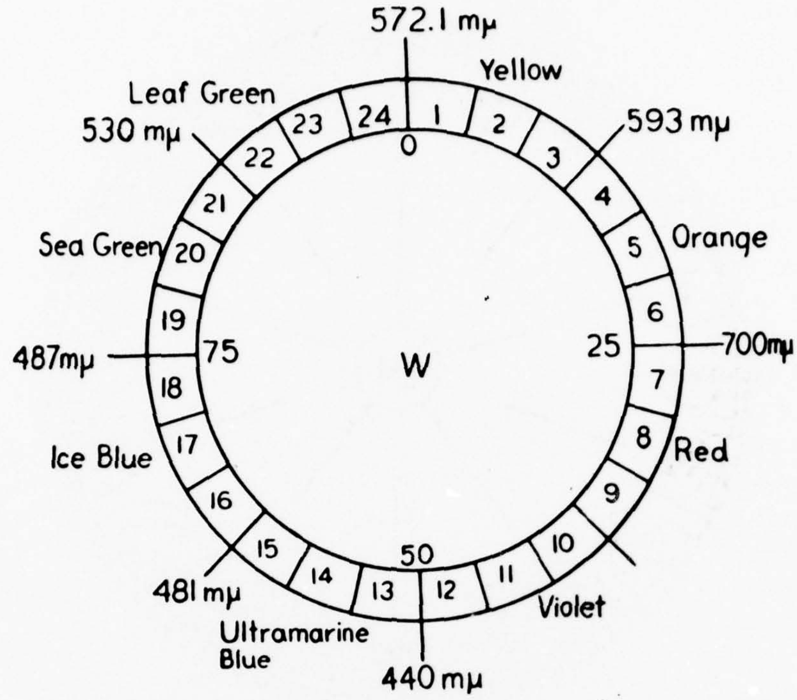


FIG. 3. Ostwald color circle.

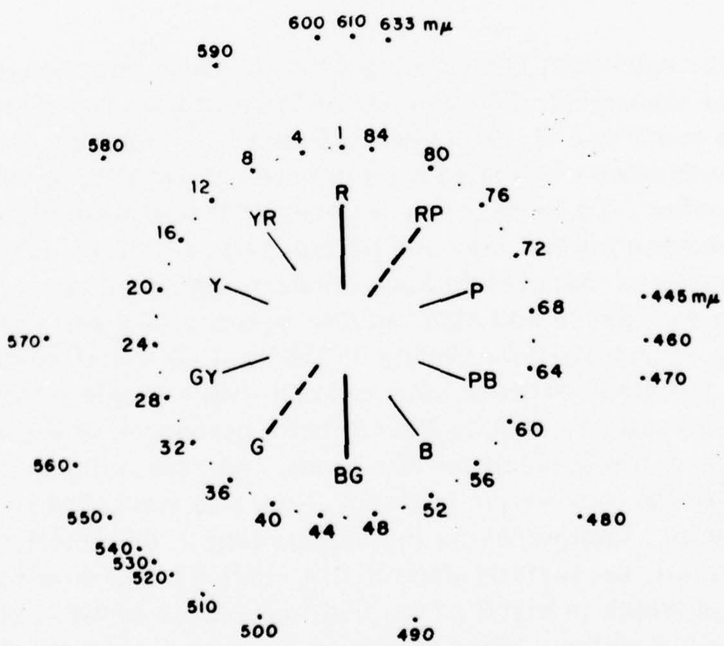


FIG. 4. Eighty-five hues of Farnsworth selection with appropriate spectrum wavelengths indicated. Green-to-redpurple, and bluegreen-to-red axes are to be noted.

lowish orange. Balanced orange is at ca. 601 mμ of the spectrum (Rubin, 1961) and Farnworth's "R" is much too close to this spectral locus. The "Y" chip in the Farnsworth selection is in its proper place, at or near 576 mμ. As far as the locus of pure Blue is concerned, one feels again that considerations of symmetry prevailed over those of sensory. The notation "B" is assigned to chip # 54, the dominant wavelength of which is given as ca. 483 mμ; while in Rubin's large sample, normals localized pure blue at or near 468 mμ, and Dimmick and Hubbard (1939) placed it at 476 mμ. Farnsworth's locus "B" is a still greenish blue. Chips # 62 to # 64 are probably purer blues.

Of course, any great rigidity in the assignment of color names to particular samples with a particular dominant wavelength is of questionable merit. Even the two just quoted data regarding primal blue indicate that there is some uncertainty as to the "exact" localization of colors in the spectrum. This uncertainty is even more obvious in the green. Chip # 36 of the Farnsworth selection carries the notation "G" (for pure Green), and its dominant wavelength is marked at ca. 525 mμ. As is known from an outstanding study by Rubin (1961), this wave length does not represent pure green for all or even for most color normals. A chip with this dominant wavelength will appear pure green to some color normals but will be an already yellowish green to possibly a majority of them, to all those for whom pure green is at or around 514 mμ; to this wavelength Farnworth's selection, chip # 39, is the nearest fitting. On the other hand, to the first, the 525 mμ, group, 514 mμ is an already bluish green. Neither is the pure green of either the deuteranomalous or the protanomalous at 525 mμ. According to Rubin's studies, these loci are at 520 mμ, and 502 mμ, respectively. All of these three loci fall into the Green-Blue, quintant of Farnsworth's pentagon. Farnsworth has, obviously for the sake of five-pointed symmetry, somewhat over-shortened both the Red-to-Yellow and the Green-to-Blue sides of what should be an irregular quadrangle (rather than a pentagon). The Blue-to-Red side which, according to his notation, runs from chip # 54 to chip # 85, is in reality not quite that long. Even if it hurts the symmetry of design, the notation "R" of the Farnsworth diagram should actually be shifted somewhat further clockwise into the region of the spectrum gap where it really belongs. Pure red is no spectrum color (Dimmick & Hubbard, 1939), and 610 mμ is far from being red. This shifting would add some chips to the quadrant between red and yellow. Similarly, the "B" notation should be shifted in the counterclockwise

direction. The five-pointed arrangement inherited from the Munsell notation system and printed into the clinical test blanks should be abandoned. It certainly adds nothing to the validity and accuracy of the test.

The 100-Hue Test, as it is known, represents a superior achievement. It is, in the experience of the author, the most versatile of all color vision tests. As far as the accuracy of analytical diagnosis is concerned, it is surpassed only by the anomaloscope, which, on the other hand, has a much narrower range of applicability. It is unnecessary to discuss here the fact that the anomaloscope is restricted in its usefulness to the analysis of red-and-green deficiencies, while the 100-Hue Test is equally well suited for the diagnosis of yellow-and-blue (or blue) deficiencies, all those rather common but, so far, much neglected deficiencies of color vision that come with certain ocular disease (or with advancing age). It must, therefore, be emphasized that the purely theoretical remarks just made will not in any way reflect on the usefulness of the test. Whatever names the entry form assigns to individual chips of the array of 85 samples used in this test does not actually matter.

Stripped from all unessentials, the Munsell and the Farnsworth circles are object color circles with four loci for the four primal colors. All object color circles have four such loci of equal rank and display certain ordered combination among the four primal hues. All have the Hering circle as their prototype—whether their originator is or was an adherent of the four-color theory or not. Yellow is always flanked by red and green, its two compatible companions, but never by blue, its opponent color. Yellow cannot be bluish. Green is always flanked by yellow and blue, its two compatible companions, but never by red, its opponent. Green cannot be reddish. And this settles the circular arrangement. There is no other way to arrange object colors. The chromaticity diagram was certainly not constructed with an eye for any circular arrangement of color. It was developed to emphasize its tri-parameter aspects. Still, it turned out to be a circle, essentially. It is a circle distorted into a horseshoe shape to agree with certain mathematical considerations but still a circle, and the Munsell arrangement of colors fits into it quite naturally (Fig. 5). There are four primal loci in it, and the same ordered combinations between hues as are to be found in any other color circle. (Numbers are added to indicate the appropriate spectrum wave lengths.) But one can go find them. Even in the spectrum, yellow is flanked by red and by green, while

blue nowhere appears mixing with yellow, and green is localized between yellow and blue, while nowhere has red any common border with it. No wave length exists which would simultaneously evoke a red and green sensation or a yellow and blue sensation. Color circle or spectrum red and green sensations are incompatible and so are yellow and blue.

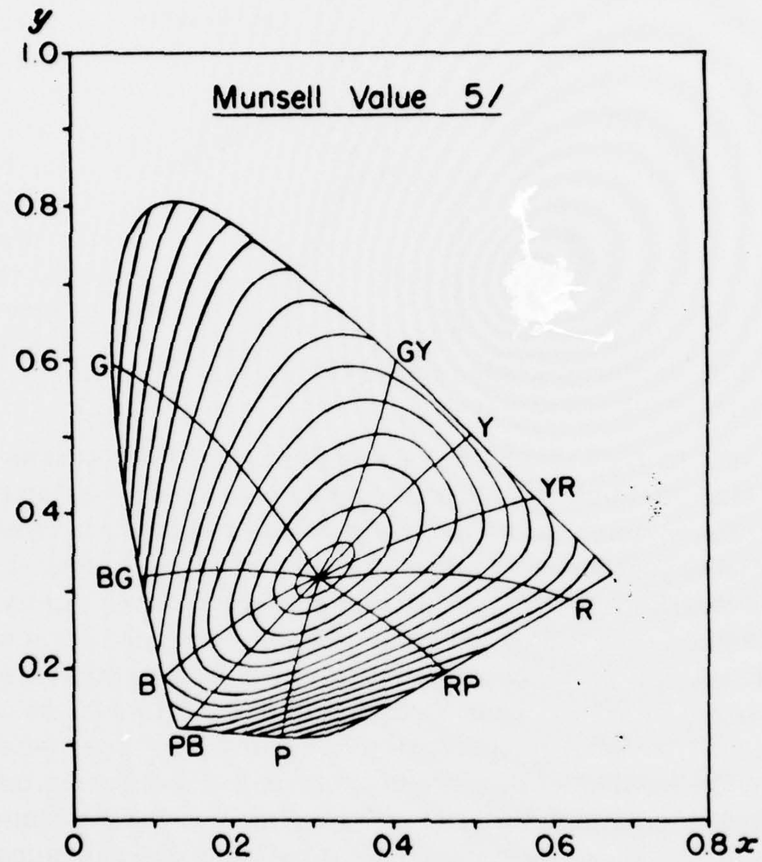


FIG. 5. I.C.I. chromaticity diagram with arrangment of Munsell colors.

The superiority of the Farnsworth circle over the original Hering arrangement rests in its factual asymmetry. The Hering circle (Fig. 6) is too symmetrical, and much too rigid in the presentation of colors.

In the Hering circle (or the Ostwald circle), opponent colors like yellow and blue are placed 180° from each other, at opposite ends of a diameter, and the two opponent color diameters (the red-to-green diameter, and the yellow-to-blue diameter) are

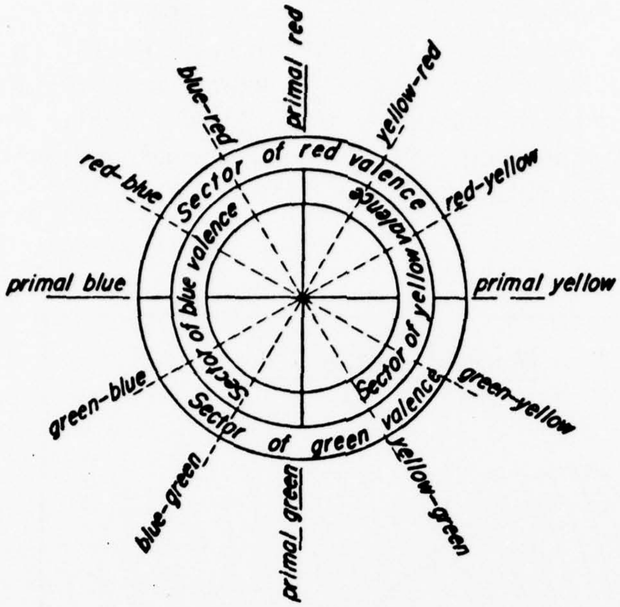


FIG. 6. Hering's color circle with two sets of opponent color crescents.

perpendicular to each other. The arrangement of the blended colors is also symmetrical, and the number of significant steps from one primal color to the next is presented as being equal. The criticisms just voiced against the Munsel circle are here even more justified. Not only is one man's green more often than not another man's blue green or yellow green, as already discussed, not only is there a certain inevitable variability in the exact locus of primal hues as determined by different observers, but it is entirely unjustified to assume any a priori equality in the number of discernible, blended hues between two given compatible primal hues. Only experiments—painstaking experiments like those first carried out by Munsell—can determine their number.

But the greatest shortcoming of the Hering circle, with its rigid four-quadrants symmetry, is that it quasi precludes the separation of the deutan and protan subtypes of red-and-green color deficiency. The same would be true of the tetartan and tritan subtypes of yellow-and-blue color deficiency. Hering's achievement, of course, was superior. His theory is basically correct—whatever the number of pigments which mediate color vision—and it turned out to have the most remarkable prediction value. It is known today that no red-blind or green-blind people exist and that, in fact, both protanopes and deuteranopes are red-

and-green-blind, even if the pigment present in the fovea of the protanope is called chlorolabe (Rushton, 1962). All this follows logically from the opponent colors theory, and so does the fact that both protanopes and deuteranopes have two opposing areas of complete lack of hue in their circle of colors. They and their anomalous cousins all "confuse" colors along opponent diameters in the color circle. Farnsworth's color vision tests make sense only if one interprets their results in terms of opponent colors. The tests clearly show that what is generally involved in a color vision deficiency is either the red-and-green diad, or the yellow-and-blue. Both Farnworth tests, the 100-Hue Test, which is the subject of this paper, and the Panel D-15 Test, are essentially tests which reveal an involvement along a diameter[1]—a diameter which connects two opponent and more or less complementary areas of the Farnsworth color circle. Obviously, all that is necessary is to forego the rigid symmetry of Hering's scheme for the more natural arrangement of colors achieved by Munsell. In the Munsell circle, and, especially in its superior variant, the Farnsworth color circle, R is not directly opposite to G. This seemingly insignificant departure from symmetry makes it in fact possible to fit into it the two red-to-green diameters that characterize the axes of color confusion of deutans and protans. (And since Y and B are also not opposite each other, it makes it possible to differentiate two yellow-to-blue diameters.) One adheres to custom by calling the deutan confusion axis the Green-to-Red purple axis and the protan confusion axis the Bluegreen-to-Red axis without attaching any great significance to these designations. They simply serve as memory aids. The essential bimodality of color specifications in the color world of the red-and-green defective had no place in Hering's scheme. The essential bimodality of all color specification in the color world of the red-and-green defective, the split into a deutan subtype and a protan subtype, reveals itself clearly and unequivocally in the two Farnworth tests. (Mutatis mutandis, the same statement can be made relative to the yellow-and-blue defects.) With a certain simplification of historical truth, one might state that Hering presented the conceptual basis for understanding the essentially opponent character of all color defects (they are either red-and-green defects, or yellow-and-blue defects), while Farnsworth, with his tests, revealed the essentially bimodal character of each of the two existing major classes of opponent color de-

1. As will be seen, it is not the same diameter in the two tests.

fects. With his arrangement of colors and with his two tests, Farnsworth made, in the opinion of the author, the greatest single contribution toward a true understanding of color vision and its defects since Hering.

The clever arrangement of the 100-Hue Test into four subsections and the entry form provided for recording purposes deserve especial added comment. As the case of the sister test, the Panel D-15 Test, the use of the proper blank form pays a maximum dividend. As one enters the test results into the record sheet provided for this purpose (how to do this will be explained somewhat later), a dichotomous axis, a diameter in the circular arrangement of the colors, emerges, so-to-speak, before one's eyes. This diameter always connects opponent circle sections, and its direction provides the essential means of diagnosis. In both the 100-Hue Test and the Panel D-15 Test, the diameters, which are, respectively, characteristic of the deutan and the protan defects run roughly in the same direction but show a bimodal distribution pattern. In both tests, the diameter which characterizes the deutan defect starts at a longer wave length than the one which gives away the protan. The diameter which is diagnostic of yellow and blue defects runs at roughly right angles. Possibly, it is also bimodal, since a subdivision of the defect into a tritan and a tetartan variety seems to become more and more justified. The color performance of a protan always parallels that of a deutan—except that the same characteristic is related to a shorter wavelength. Take any kind of a performance at random: the primal yellow of the deuteranomalous is at 583 mμ, that of the protanomalous at 563 mμ (Rubin, 1961); the balanced orange of the deuteranomal is at 612 mμ and that of the protanomalous at 590 mμ (Rubin, 1961); the locus of best wavelength discrimination of the deuteranomalous (which will be discussed later) is around 500 mμ and that of the protanomalous around 450 mμ (Nelson, 1938); the area of complete spectrum desaturation of the deuteranope (which will also be discussed later) is around 498 mμ, that of the protanope near 492 mμ, etc. (Walls & Hack, 1956).

Farnsworth divided the 85 chips into four sections, and he did not do this for convenience of handling. (The subdivision is indicated in Fig. 1). It is one of the most clever, even brilliant, features of the test. Chips # 84 to # 22 constitute the first section, chips # 21 to # 43 the second, chips # 42 to # 64 the third, and chips # 63 to # 85 the fourth. There is a necessary reduplication at the beginning and the end of each section. Since roughly

only one-fourth of the color circle is presented at any one time, a color-defective subject will never be given a chance to "confuse" red with green, or yellow with blue. This he would do only when confronted with a selection from all wavelengths, as in the Panel D-15 Test. It has been mistakenly suggested that the 85 chips be presented to the condidate for testing all at once. This would only transform the 100-Hue Test into a more difficult Panel D-15 Test. It would show which opponent colors a color defective confuses. However, the 100-Hue Test is not an opponent-color confusion test, it is not just a glorified 15-Hue Test. In the 100-Hue Test the examined subject is asked to compare and arrange a *limited number of similar hues, not opposing hues.* And, in contradistinction to the Panel D-15 Test, there are two fixed "reference" chips provided in each quadrant—the two samples that are farthest apart in hue within the just-presented-quadrant. In the first section, chips # 84 and # 22 are fixed white chips, # 85 to # 21 are loose and are to be arranged between the two reference samples. In the second section, # 21 and # 43 are fixed, and # 22 to # 42 are to be arranged, etc.

The following discussion is restricted mainly to the performance of deuteranomalous and protanomalous subjects, since they are the major interest[2]. However, in order to make their performance in the 100-Hue Test more understandable, the principle of construction of the Farnsworth color circle should be once more discussed from a somewhat different point of view. I must digress here somewhat and deal with some of the now classic studies of Wright and Pitt (1934), Nelson (1938), and of McKeon and Wright (1940) on the ability of the normal, the deuteranomalous, and the protanomalous subject to discern changes in spectral wavelength by a just noticeable difference in hue.

At first glance, the arrangement of wavelength numbers around the Farnsworth color samples seems rather haphazard. There are sections where the wavelength markings are far apart, and others where they are crowded; and the longest and the shortest spectral wavelengths are actually missing. This latter circumstance should really not be unexpected. Wavelengths longer than ca. 630 mμ all have the same hue (Purdy, 1931). They have no

2. It is becoming more and more evident to the author that, in the study of the not altogether rare yellow-and-blue defects due to ocular pathology and to the aging process, the 100-Hue Test will also turn out to be the most preferred color vision test. However, there is not yet sufficient material to deal with this part of the subject.

place in a Munsell circle. They have little space assigned to them on the chromaticity ogive. And the same is true of the shortest wavelengths. As already been discussed, the Farnsworth arrangement of chips has, in essence, retained the most outstanding feature of the Munsell system, based as it is on the principle of the "just noticeable difference in hue" without a priori reference to any differences in wavelength. Different wave lengths with identical hues are not represented in it.

A normal subject (that is, a young, normal subject) is not expected to make any substantial error in arranging any or all of the four panels, because every single chip is different from its neighbor of the next higher and of the next lower serial number by that just noticeable difference in hue. It is this very feature of the Munsell arrangement which Farnsworth has turned into a most sensitive, diagnostic tool.

To give one example: normal subject is expected to place chip # 28 on one side of chip # 27 (and nearer to the reference chip # 43 of section 2), and chip # 26 on the other side of chip # 27 (and nearer to the reference chip # 21 of the same section) because chip # 28 is a just noticeably more greenish green-yellow, and chip # 26 is a just noticeably more yellowish green-yellow than chip # 27. The difference in the dominant wavelength of these three chips, as such, is irrelevant.

One may haphazardly choose another example, say a triad of purple chips from section 4 that do not correspond to any single spectrum wavelengths. If chip # 78 is a reddish purple (which, of course, means a predominantly reddish red-blue), then chip # 79 must be a just noticeably more reddish red-purple, and chip # 77 a just noticeably more bluish red-purple. Moreover, chip # 77 has to be placed on one side of chip # 78 (nearer to the reference chip # 84), and chip # 79 on the other side. To a normal subject the test offers no freedom of choice. If he is normal he cannot make any significant errors.

An important restriction has to be made here. Extensive studies by Verriest (1963; 1964) suggest that this statement holds only for the normal young adult. Children under the age of ca. 14 years make some errors, especially in the blue-green. (Those are sometimes difficult samples to tell apart.) More significant, and rather constant, is the deterioration of the hue-discrimination faculty in the middle-aged and aged, actually starting in the forties of life. The faculty of arranging the Farnsworth samples correctly deteriorates, especially in the region of chips # 35 to # 50, the green to blue-green areas of normal

subjects, and, to a lesser extent, also in the region across the diameter of this area, in the region of chips # 82 to # 5. It is quite likely that the cause for this lessened sensitivity, especially in the first of the two regions, is due to enhanced absorption of shorter spectrum wave length by the refracting media, especially the sclerosing crystalline lens.

Farnsworth introduced a very ingenious method of recording the results of the 100-Hue Test. His blank for recording (Fig. 7) represents the color circle of 85 members with the different good and not-so-good features which are by now thoroughly familiar. In addition, this "color circle" is surrounded by a number of other concentric dotted circles.

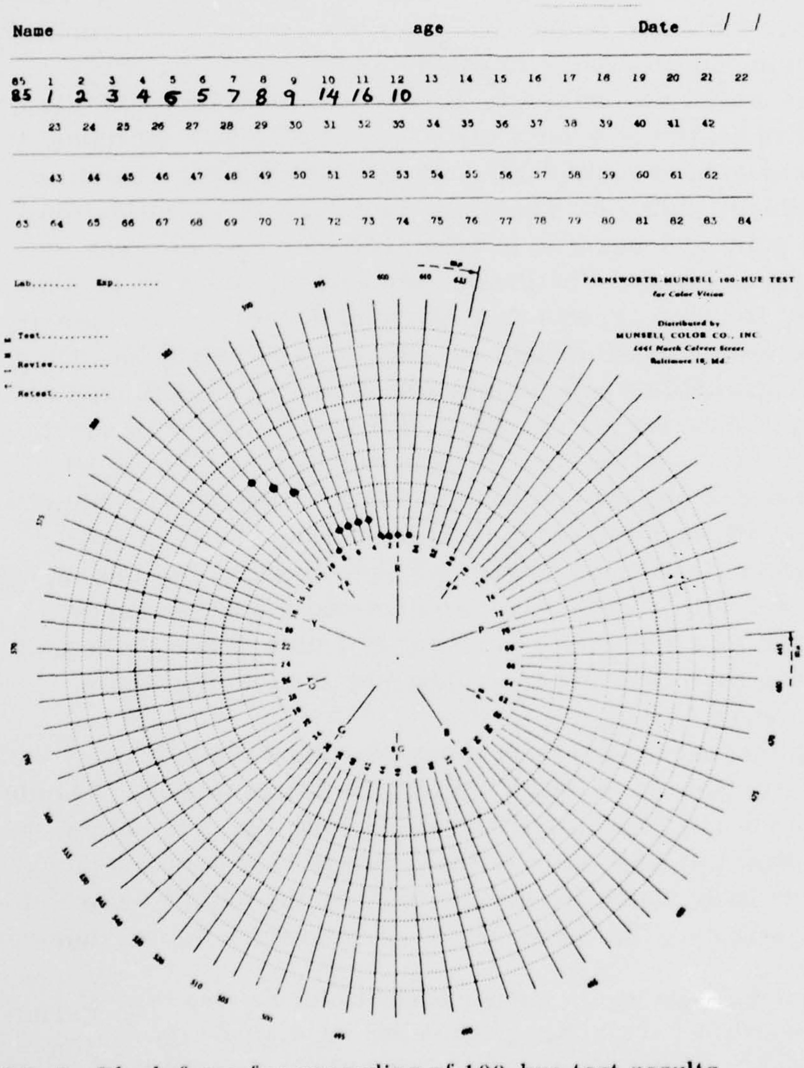


FIG. 7. Blank form for recording of 100-hue test results.

Assume that a subject has arranged the first several chips of the first section in its proper order starting from the reference chip # 84. In this case, chip # 85 is placed between # 84 and # 1, at its shortest possible "one-chip," or "one-unit," distance from each. Similarly, chip # 1 is placed between # 85 and # 2; chip # 2 between # 1 and # 3, etc. The result is recorded by dots opposite the appropriate locus numbers. Since there was no error the score points are placed nearest to the circle of loci on what is usually designated the two-chip-distance circle and what actually is the zero error circle.

Assume, furthermore, that the subject did not place some of the following color chips of the section in their proper order but in the order indicated in Fig. 7. Thus, into locus 10 he placed the # 14 chip and into locus 11 the # 16 chip, etc. The error score then starts with chip # 9. It is found, then, that chip # 9 in locus 9 is placed at 5 units instead of 1 unit distance from one of its neighbors (chip # 14), and at 1 unit distance from its other neighbor, chip # 8. The error is 5 + 1 - 2 = 4 units, and the score point at locus 9 is to be placed four circles away from the zero error circle. Continuing, one finds in locus 10 an error score of 5, in locus 11, an error score of 6, etc.

An interesting detail of this scoring is to be noted. Errors are self-aggrandizing and cumulative. Take the example of the samllest possible error: two chips, # 5 and # 6, were interchanged in loci 5 and 6 (Fig. 7). This means that chip # 6 in locus 5 is now 2 distance units from its first neighbor (# 4), and 1 distance unit from the other (# 5). The error is 2 + 1 - 2 = 1 unit. However, by necessity chip # 5 (now in locus 6) also scores an error of 1 unit. Moreover, chips # 4 and # 7 which are in their proper loci also score an error of 1 unit. Thus, an error score of 4 units has been accumulated by this smallest of all possible errors.

If the interchange occurs between two chips farther apart then, by necessity, two error peaks will manifest themselves. Assume that, in loci 8 and 14, chips # 8 and # 14 turn out to be interchanged. How this will show in the score is best demonstrated on an error table which is actually used by the author before entering the scores. This table has to be read from below, upwards[3]:

3. Professor Verriest uses a similar error table. He also adds up the error score and, in the example given in this table, would speak of an error of 40 points. He finds this number score useful for evaluation of the error's magnitude. The error diagram is still the author's preference.

Error score:	0	6	10	4	0	0	0	4	10	6	0
Distances:	1	7	5	1	1	1	1	5	7	1	
Chips:	6	7	14	9	10	11	12	13	8	15	16
Loci:	6	7	8	9	10	11	12	13	14	15	16

It should be understood that this is a made-up example. Such an error will never occur. If it should happen that chip # 14 is placed into locus 8 next to chip # 7, then the chip will pull its similar neighbors, maybe # 13 and # 15, with it. As emphasized in the author's essay on color vision, no color defective ever makes haphazard or senseless errors (Linksz, 1964).

As seen, in this example, scoring errors are also self-procreating. Once a subject has placed one chip into a wrong place, or left out a chip, he is faced with the task of placing the chip which he has not used into another, by necessity, wrong locus. One may often watch a color-defective candidate fumbling around with a left-out chip and can, from his facial expression, almost tell that he placed it only the best he could. He would have liked to leave it out entirely, but the observer must insist that all chips be placed.

Recording the errors in the arrangement in the just described method, it turns out that in the case of a color defect, any type of color defect except possibly those caused by senescence, errors "pile up" in two opponent regions of the Farnsworth circle. It is the direction of the diameter which connects the two error piles which gives the diagnosis away. What determines this direction is what now must be investigated.

The job of one's arranging the 100-hue samples corresponds, in many respects, to a differential hue sensitivity test. What is essentially the same facilty, viz., the differential hue sensitivity for spectrum colors, has been investigated repeatedly. The classical data are those of Wright and Pitt (1934). These authors studied the spectrum, not pigments, and related the just noticeable difference in hue to spectral wavelengths. They found areas, notably two of them (Fig. 8), where small changes of wave length cause noticeable change in hue, and other areas where one has to change the wavelength considerably before the hue changes just noticeably. It is in the nature of things that this difference will mirror itself in the relationship between the object color circle on the one side, and the spectrum circle on the other. This relationship is demonstrated in the Farnsworth diagram in which, as in the test itself, there is nothing haphazard. The

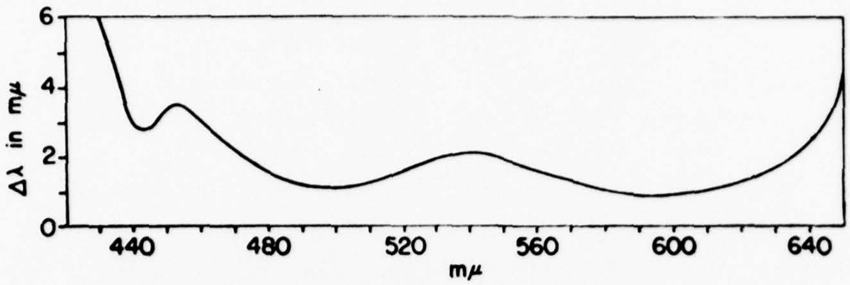


FIG. 8. Wavelength sensitivity (hue sensitivity) curve of normal observer (data of Wright & Pitt).

criterion is "just noticeable change of hue." One will, therefore, understand that into the two spectral areas in which wavelength discrimination is best, a great number of Munsell colors must be crowded. The opposite is to be expected for spectral areas where there is little change in hue with considerable change of wavelength. These regions in the Farnsworth selection are represented by only a few samples. Comparison of the curve of wavelength discrimination (Fig. 8) and the Farnsworth color circle (which in Fig. 9 has been stretched into a straight line, just for the purpose of this comparison) clearly show the parallelism. In the wave-length discrimination curve of Wright and Pitt there is one area of maximum sensitivity in the region of ca. 499 mμ. In the curve, this is represented by a minimum, since the needed change in wave-length for the appreciation of change is minimal. In the Farnsworth circle, the same area is broadly represented. Take, e.g., chip # 42 which corresponds to 500 mμ, while 470 mμ corresponds to chip # 64. There are, in other words, more than twenty discernible steps between these two wavelengths. The second maximum of the curve by Wright and Pitt occupies the area around 590 mμ. Here, again, there is broad representation. Chip # 46, e.g., in the Farnsworth selection, corresponds to 590 mμ, and the chip corresponding to 570 mμ is # 23. Here there is room for seventeen steps over a stretch of no more than 20 mμ.

FIG. 9. Linear arrangement of Farnsworth selection of colors with appropriate spectrum wavelengths indicated.

The reader will note that the Farnsworth circle has been somewhat arbitrarily cut at chip # 76, at a locus which seems

to be about in the center of the spectrum gap. This gives the diagram a certain symmetry and leaves the extremes of the spectrum, where wavelength discrimination is poorest, widely separated. The reader will also note that in the straightened Farnsworth diagram the wavelength numbers had to be given in decreasing order to correspond with the increasing Farnsworth numbers. In the diagram by Wright and Pitt, the order of colors is reversed and the wave-length numbers give an ascending scale. This should impose hardly any difficulty in understanding and comparison.

Scrutinizing the Farnsworth circle (Fig. 9) with this newly gained insight, one must note that the two areas of best wavelength discrimination, the section between 590 mμ and 570 mμ, and the section between 500 mμ and 470 mμ, occupy, as if by chance, two opponent sections of the circle. This is just one more small point which shows the essential soundness of Newton's and Hering's circular arrangements. A color circle is a "natural." Even such loci as the maxima of Wright and Pitt arrange themselves in an opponent fashion. This feature remains hidden in the usual diagrams. Color vision data become more meaningful if they are arranged on a circular diagram rather than into Cartesian coordinates. As is seen repeatedly, the usual presentation of color vision data along Cartesian coordinates actually hides some of the important facts of color vision. A set of curves like the two lower curves shown in Fig. 10 would never suggest that in the color world of the deuteranomalous and protanomalous there are two areas of especially poor saturation. The Panel D-15 Test works only because there are two. And a set of curves like those presented in Fig. 11, a and b, will not suggest that in the color world of the deuteranope and protanope, there are two areas of best wavelength discrimination. The 100-Hue Test shows that there are two. The dichotomies which are the diagnostic characteristics of the two Farnsworth tests remain hidden, totally unexpected, even inexplicable to those to whom the spectrum is a straight line leading from nowhere to Erewhon, hitting these keys as it proceeds.

The section of the Farnsworth double circle where wavelength notations appear most crowded is the section between 540 mμ and 520 mμ. This section is quite poorly represented in the object color circle, and, altogether, three chips, # 35 to # 37, take care of 20 mμ. The colors opponent to this section fall within the spectral gap.

We are ready to turn our attention toward the red-and-green

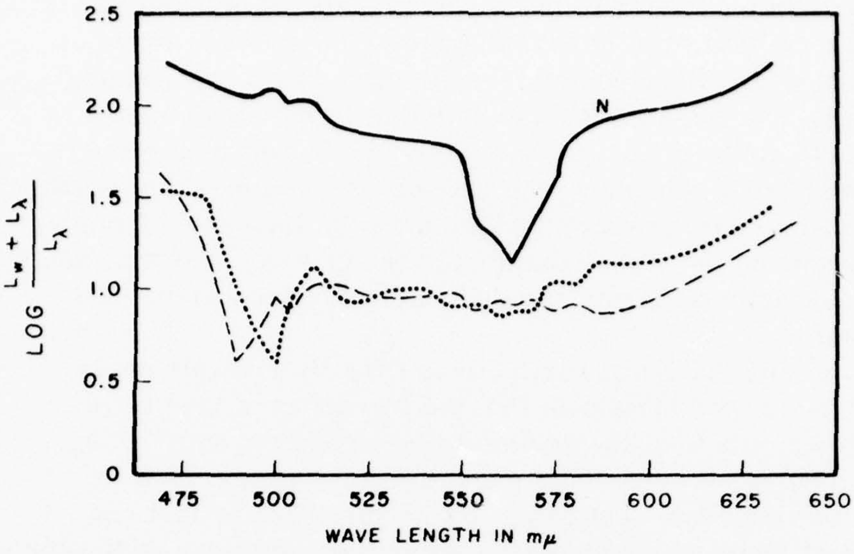


FIG. 10. Chapanis' diagram indicating loci degree of intrinsic saturation of spectrum colors in normal (upper curve), and also in deuteranomalous and protanomalous (lower curves) with bimodal distribution of mixima.

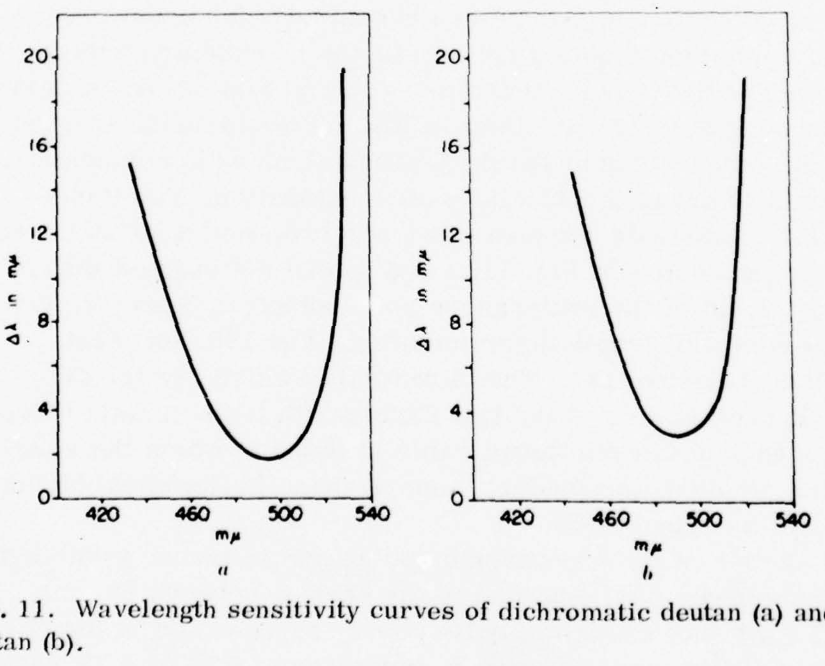


FIG. 11. Wavelength sensitivity curves of dichromatic deutan (a) and protan (b).

defectives and to try to analyze their performance in the 100-Hue Test. One must remember that red-and-green anomalous subjects, both subtypes, are trichromats. Their spectrum of

color and their circle of colors are built upon the normal foursome of valences. They see red, yellow, green, and blue like normals, though they localize their pure colors in somewhat different loci of the spectrum or the circle. Another difference which exists between the normal and the color anomalous is a difference of variety. The color world of the anomalous is just a more monotonous color world. Curves taken from Nelson (1938) and from McKeon and Wright (1940) and here combined Fig. 12 show[4] that, like the normals, the red-and-green anomalous also have two principal areas of best wavelength discrimination and that the localization of these two areas is essentially

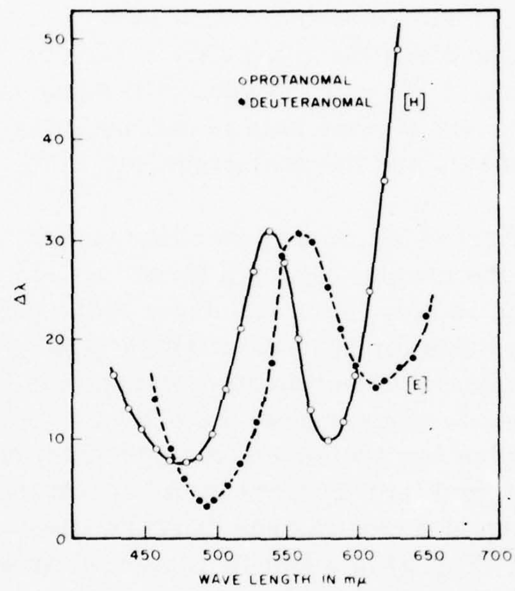


FIG. 12. Samples of wavelength discrimination curves in deuteranomaly and protanomaly.

bimodal. They are represented by longer wavelengths (ca. 500 mμ and ca. 610 mμ) in the case of deuteranomaly and by shorter wave lengths (ca. 450 mμ, and ca. 580 mμ) in the case of the protanomalous. It is needless to emphasize that these respective loci occupy practically opposite ends of diameters across the Farnsworth color circle. What these curves also clearly demon-

4. This diagram was actually taken from a publication by Hurvich and Jameson (1960). A similar combination diagram was also published by Nelson.

strate is that the wavelength discrimination of the red-and-green anomalous is, even at its best, poorer than that of the normal. (The maxima are further from the abscissa than in the case of the normal.) The red-and-green anomalous discern a smaller number of hues in their spectrum.[5] The two areas of best wave-length discrimination of the normal are over-represented as far as the red-and-green defectives are concerned. One will almost expect them to make mistakes in arranging samples in these two over-represented areas—one essentially blue, the other essentially yellow. One will, of course, also expect the errors to show a bimodal distribution.

It is in large part due to the work of Rubin (1961), to which reference has been made repeatedly, that there is now some accurate information about the essentials of the color distribution in the spectrum of the two subtypes of red-and-green deficiency. These data will further help in understanding the scores of the deuteranomalous and the protanomalous in the 100-Hue Test.

There exists, first of all, a very peculiar and rather distinctive difference in the manner in which these two subtype localize blue—inasmuch as only in the spectrum of the protanomalous is there a definite locus for pure blue, which gradually turns into greenish blue in one direction and reddish blue (violet) in the other direction. In other words, the red valence returns in the short-wave end of the protanomalous spectrum beyond the locus of pure blue, just as it returns in the spectrum of the color normal. The return of a new valence mirrors itself in the curve of Wright and Pitt (Fig. 9) in a sub-maximum at around 440 mμ. Sensitivity to wave-length change always improves when the hue gets mixed, and so it does here where, suddenly, more reddish and more bluish violet colors come up for comparison. In contradistinction, the deuteranomalous sees no violet. For him, the short-wave end of the spectrum just fades out, but remains essentially the same blue.

How this difference manifests itself in the wave-length discrimination curve of the two defect subtypes has not yet been actually investigated. (One has to be aware of a question before

5. Most spectrum colors also appear to them relatively desaturated (Nelson, 1938; McKeon & Wright, 1940; Chapanis, 1944). The two lower curves in Fig. 10 belong to a deuteranomalous and to a protanomalous subject, respectively. Their lower level indicates their lower intrinsic saturation.

one can look for an answer.) In the differential diagnosis of the two subtypes of red-and-green deficiency with the 100-Hue Test, this difference plays a definite role. As one sees from Farnsworth's data (Fig. 13), poor color discrimination by the deuteranomalous has one of its two peaks—it might be called the "blue

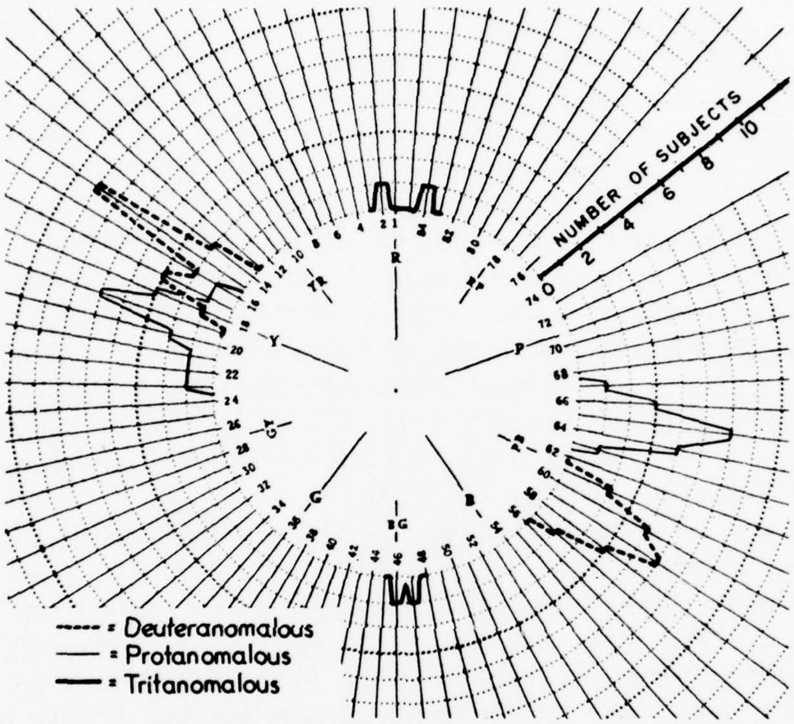


FIG. 13. Distribution of maximum error loci in 100-hue test in deuteranomaly, protanomaly, and tritoanomaly.

error peak"—in the region of chips # 58 to # 60, where, for normals, blue is expected to be turning into violet. In the Farnsworth nomenclature, violet figures as purplish blue. Color discrimination by the protanomalous is better in this region. For the latter, the "blue error peak" is nearer to the purples in the region of chips # 64 to # 66. For a protanomalous, with his lessened capabilities of hue discrimination, hues of this region are greatly over-represented, and an accumulation of errors will not be expected. Several protanomalous subjects have told the author that "frankly" they saw no difference at all between a great many chips in this region. They just arranged them in a random fashion. Figure 12 also indicates that, in the region of the spectrum around 440 mμ, the region where normals have their third area of relatively good color discrimination, the

protanomalous actually did better than the deuteranomalous. As the curves demonstrate, below ca. 450 mμ the deuteranomalous subject suddenly did very poorly: Obviously, all blues appeared to him the same blue. In general, deutans do poorer than protans in the blue error area of the 100-Hue Test. They also did poorer in Nelson's hue discrimination experiments (see, e.g., figure 13 of his paper, 1938).

Rubin's investigation also furnishes pertinent data about the locus of balanced orange, pure yellow and pure green in the spectrum of the red-and-green anomalous. Reference has already been made to some of these data with emphasis on how all of them reveal the bimodal distribution of wavelength values which is the characteristic link between the deutan and the protan defect. Every one of these loci carries a longer wavelength number in deuteranomaly, a shorter wave-length number in protanomaly. Pure yellow, according to Rubin's figures is located at 576 mμ. The pure yellow of the deuteranomalous and the protanomalous saddle this locus (Nelson, 1938). The former finds it at a longer wavelength, at ca. 583 mμ, the latter at a shorter wave-length, at ca. 563 mμ (Rubin, 1961).

As it was practically predicted the discrimination of the red-and-green defective is poor in this other over-represented region of the Farnsworth circle as well. There is a "yellow error peak" (Fig. 13) to their performance in the 100-Hue Test, and it is not surprising to find that this peak, too, is bimodal, that for the deuteranomalous it falls into a region with smaller chip numbers (representing longer wavelengths), while the peak for the protanomalous falls into a region with larger chip numbers (which represent shorter wave lengths).

Motokawa (1951) has repeatedly emphasized that, in the spectrum of the red-and-green defective, yellow is the most brilliant section. Still, wavelength discrimination is poor in this region. The two statements should not, however, be looked upon as contradictory. Yellow might be a brilliant color in the spectrum of the color defective, but in the Farnsworth selection there are so many samples of similar wave lengths, especially in the 580 mμ to 570 mμ region, that to the color defective, whose wavelength sensitivity is, even at its best, poor, there are just too many of them.

Once more, it must be understood that poor performance in the 100-Hue Test is not caused by desaturation in the error areas. Desaturation is the cause of false choosing in the Panel D-15 Test. One of the handicaps of the red-and-green defective is the

lack of variety of hues even in the areas which are relatively speaking, not desaturated. It is this factor which, by its clever arrangement, the 100-Hue Test turns into a means of diagnosis.

As can be seen from the diagram published by Farnsworth (Fig. 13) the maximum error score of deuteranomalous subjects runs in the average between chips # 15 and # 59, i.e., roughly between the wavelengths 580 mμ and 480 mμ. The corresponding diameter for protanomalous subjects runs between chips # 19 and # 65, i.e., roughly between the wavelengths 575 mμ and 460 mμ. There is probably no need for further gilding this particular lily. Deutans and protans always, under all circumstances, in all their characteristic performances, behave in similar ways. They are subtypes only of one major class of color deficiency *in which the red and the green color modalities are chiefly affected.* All their error scores are linked up with opponent areas in a properly arranged color circle. There is one essential difference between the two subtypes: if you analyze any one of their performances in terms of the spectrum, there will be a definite bimodal distribution to the range of wavelengths to which the particular performance is associated, and the protan defect will always be associated with the shorter of the two wavelength modes.

Once more attention must be focused upon the seemingly strange fact that the red-and-green defective has a blue error peak and a yellow error peak in the *100-Hue Test*. The fact seems to offer some conceptual difficulty. Should one not expect error peaks in the red and the green in subjects whose defect is in the red and the green?

The 100-Hue Test was administered (by the author) the other day to a rather extreme deuteranomal whose job, of all things, was color-matching in a textile printing establishment. He fought for his future job security with all the sophistication of many years' accumulated experience. He insisted on checking his own score and said how silly it actually was to "accuse" him of a red-and-green defect when obviously, he scored excellently in the red and the green regions of the test, and the only mistakes he made were in the yellow and the blue. I studied some of the material this color defective had brought with him to show how well he was doing and strangely, or not so strangely, he did quite well in the blue.[6]

6. In the essay on color vision and clinical color vision tests (Linksy, 1964; see esp. pp. 99-100) it is explained why and how that legendary "color defective textile executive" is really able to differentiate certain colors almost better than normals do.

There is, obviously, more behind the existence of that yellow-and-blue error score than just over-representation. One must also understand why in the 100-Hue Test those with a red-and-green defect actually make so few errors in the red and the green. It will be easiest to explain this on the example of the red-and-green defective dichromat. An analysis of their wavelength discrimination faculty should furnish the proper answer.

The bimodal character of this faculty becomes immediately apparent if one looks at the by now classic data of Wright (1947). Figure 11, a and b, shows the wave-length discrimination curve of the deuteranope and of the protanope, respectively. The only difference between the two practically identical curves is that in the case of protanopia the peak of sensitivity manifests itself at a somewhat shorter wavelength. In neither case is the peak in the blue or the yellow. It is in the region where green is missing.

Deuteranopes and protanopes are dichromats. Their spectrum contains two hues only—a "warm" hue which, with some confidence, one may call yellow[7], and a "cold" hue which, with even greater confidence, one may call blue. The "warm" and the "cold" spectrum regions are separated from each other by a region of zero saturation, a neutral point. The existence of such a spectrum neutral point can be predicted on the basis of Hering's theory, and can well be visualized by looking at his diagram of crescents (Fig. 6). What one can also predict, and what data like Wright's completely fail to indicate, is the fact that in this color circle there are two neutral points. As mentioned earlier, the only detail Hering missed was that of the bimodality of these neutral points. This is why he could not in a satisfactory manner explain the existence of two subtypes of red-and-green blindness. The neutral spectral loci are rather close to each other: according to Walsh and Heath (1956) they are at ca. 498 mμ and 492 mμ. Still, they are so distinctive in their position that localization of the spectral neutral point is, in itself, a sufficient characteristic on which to make a differential diagnosis. And once more, in the dichromaticity of the deutan subtype, the neutral point has the longer wavelength. A glance at the Farnsworth double circle or the chromaticity diagram will show that, in spite of their closeness to each other, the two points can be easily differentiated.

7. If it would in the smallest measure please the manes of my late friend, Gordon Walls, I would concede that it does not matter. Being an ardent trichromaticist, he could not believe that a deutan or protan dichromat could ever see yellow.

The 10 mμ stretch between 500 mμ and 490 mμ is quite well represented in the 100-Hue Test. The dominant wave length of chip # 43 is, roughly, 498 mμ, and that of chip # 49, 492 mμ. The first of these chips appears colorless to the deuteranope, the latter colorless to the protanope. They are also very well separated on the chromaticity diagram. The y (abscissa) value of 490 mμ is less than 0.3, that of 500 mμ is over 0.5 (Fig. 14).

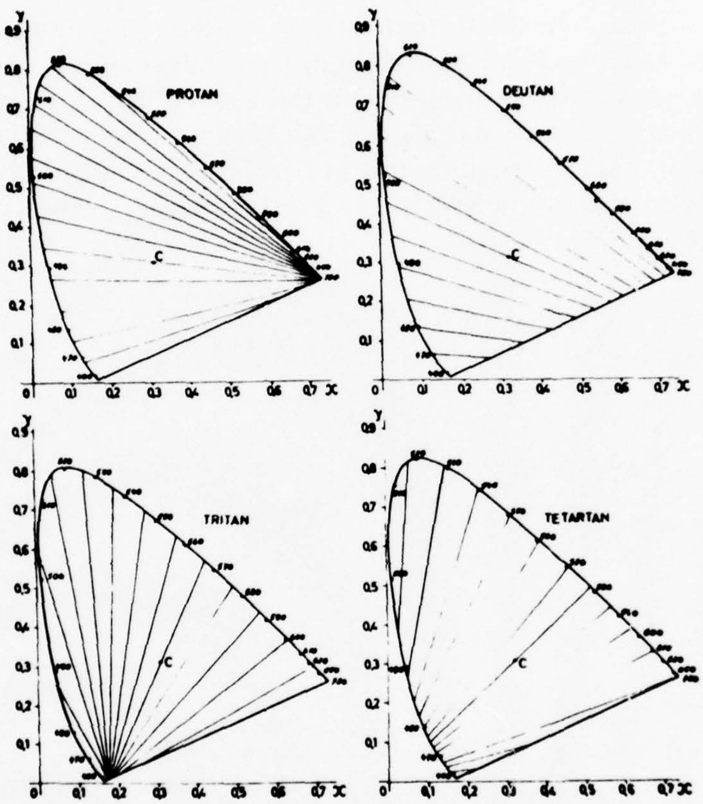


FIG. 14. Chromaticity diagrams with confusion (iso-color) lines indicated. In each case line through "C" (white or grey) connects spectrum regions of maximum desaturation.

A comparison of the locus of best wavelength discrimination and the locus of maximum desaturation in the spectrum of either type red-and-green defective dichromat reveals that the two are actually identical. In the deuteranope, 498 mμ is the spectrum neutral point, the area of maximum desaturation. But the same locus is also the locus of best wavelength discrimination, because the deuteranope can, in this region, easily differentiate the yellowishness (warmishness) of wavelengths even slightly longer against the bluishness (coldishness) of wavelengths which

are slightly shorter. The chromaticity diagram with its isocolor lines for deuteranopia (Fig. 14) is most instructive. It shows that, in the case of deuteranopia, the main iso-color line runs from 498 $m\mu$ in the spectrum through "C" and toward a point in the spectrum gap. (The spectrum gap is represented by the line which connects the two extremities of the spectrum ogive and after a fashion completes the distorted color circle.) This main iso-color line connects the loci of maximum desaturation, the areas of no-color. It is the main line of confusion. Although it is not a line running from the locus of pure spectral green, one can, with a good grain of salt, call it the Farnsworth Green-to-Red-purple axis. Above this line is the domain of the deuteranope's "warm" color, below that of his "cold" color. The loci just above and just below 498 $m\mu$ can be, therefore, easily differentiated.

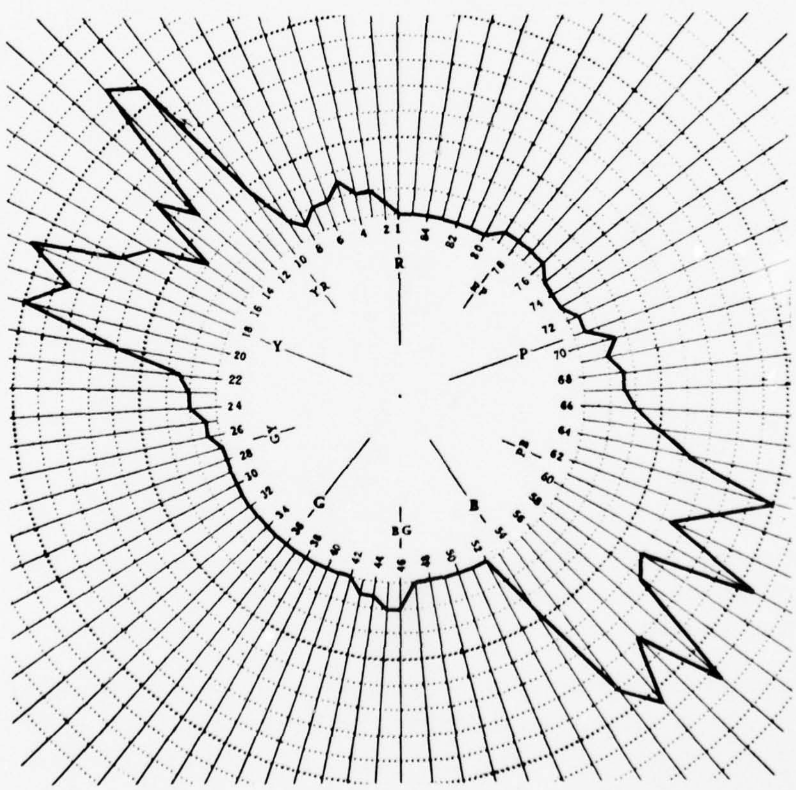


FIG. 15. Example of deutan score with 100-hue test.

As already mentioned, color chip # 43 has just about this dominant wavelength. No error in the arrangement of the chips can, therefore, be expected in this region. One can see this in Fig. 15, the score of a case of deuteranopia presented by Farns-

worth. Around chip # 43 the *deuteranope makes no error*. In this region his hue discrimination is as good as that of the normal. For the benefit of those who look naively at the performance of the so-called color-blind, it must be emphasized that it has not been said: "His hue discrimination is normal." The deuteranope does not discriminate, say, 502 mμ against 498 mμ, because the first one is to him a more greenish, the second a more bluish blue-green, as it is to the normal. His hue discrimination is not normal, even if his wavelength discrimination in this is as good as that of the normal.

Here is one of the points where there is a need to separate practice from theory. If the differentiation of the hue of, say, chips # 42, # 36, and # 30 is the criterion by which certain coded wires have to be connected properly, then one can expect that even a deuteranope will do this properly. What clues he uses for differentiation does not, for practical purposes, matter.

A glance at the 100-Hue score of the deutans and protans will reveal that there are certain regions in the object color circle where even the latter are safe. It should be the task of the industrial color scientist to elaborate on these areas and, if feasible, develop a coding system in which more industrial workers are safe.

Of course, one must not belittle the problem. As the iso-color lines remind one, a deuteranope might be able to discriminate between, say, 490 mμ and 498 mμ (which is fine), but he cannot discriminate between the latter wavelength and 650 mμ (which is a catastrophe). The 100-Hue Test avoids this issue. The Panel D-15 Test confronts one with it. The 100-Hue Test is an excitingly interesting test because it permits some insight into the workings of defective color vision. It also is a first-rate diagnostic test. But only in a limited way is it a performance test.

The spectrum locus 498 mμ in the chromaticity diagram is at one end of the iso-color line which marks complete desaturation. It represents one neutral spectral point. The locus where this line cuts the "purple line" represents, in a sense, a second neutral spectral point. Actually, the point is in the spectrum gap and this is why spectrum color scientists missed its existence. Here, again, the superiority of the circular arrangement of color data shows itself very clearly. In the real spectrum of the deuteranope, there is only one neutral area, the area found in both the wavelength discrimination and the neutral point investigation, while in the color circle there are two. This follows from Her-

ing's theory and can be predicted looking at his diagram. The two areas are again on opponent ends of a dichotomous axis. Each end of this represents an area where the hue discrimination of the deuteranope is good, where in the 100-Hue Test he makes no error. A glance at Farnsworth's published score (Fig. 15) verifies this. The errors pile up in a diameter which is at right angles to the diameter between two neutral points, in the very regions where, to the color-blind, colors appear most vivid, in the region of his best "warm" color and his best "cold" color, in the yellow and the blue, in the two regions which at the same time are, in a sense, over-represented in the 100-Hue circle.

Little has to be added to understand the performance of the protanope in the 100-Hue Test. His case is just another variant of the red-and-green defective dichromacy. His neutral spectrum area is at, or near, 492 mμ. As Wright's data testify, the area of best wavelength discrimination by the protanope coincides with this area (Fig. 11 b). Spectrum data indicate only one neutral point. In the full object color circle there is, of course, another area of complete desaturation to be found, and another area of maximum hue sensitivity at the opponent ends of a dichotomous axis. The axis starts at a shorter wavelength than 498 mμ. Thus, the protanope's dichotomous axis shows itself once more as the deuteranope's bimodal twin. And for the sake of conformity, one might agree to calling this axis the Blue-green-to-Red axis of desaturation. In the chromaticity diagram of the protanope (Fig. 14), the line of complete desaturation runs from the 492 mμ point through "C." It is shown to terminate in the "red" corner of the horseshoe, the area where the protanope's vision is notoriously poor.

The protanope has, as is known, one added distinctive feature not shared by his partner in red-and-green blindness, the deuteranope. The protanope has a foreshortened spectrum. He is practically blind for the longest wavelength of the spectrum visible to trichromats (and also to deuteranopes). As it is, this long end of the spectrum is not represented in the Farnsworth selection. This might be the reason why the protanope's diameter of best performance is slightly bent (Fig. 16).

Errors in the performance of the 100-Hue Test again pile up at opposite ends of a diameter which is roughly at right angles to the poorest saturation-best performance axis. One terminus of the diameter is in the area which to the protanope appears yellow; the other terminus is in the area which to the protanope appears blue. These opponent areas have color, but their color

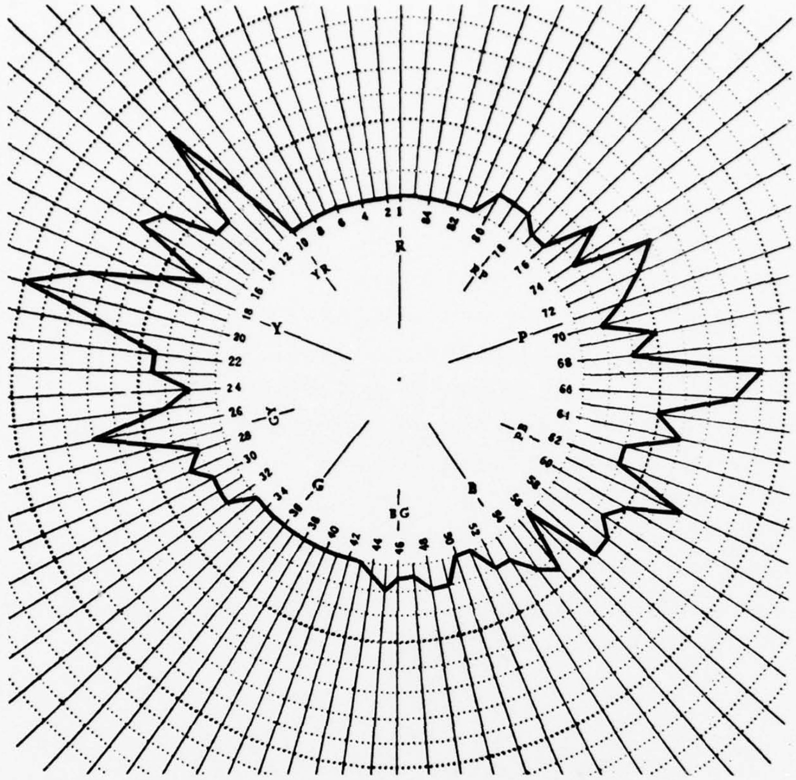


FIG. 16. Example or protan score with 100-hue test.

is monotonous: in each of the two areas many samples have the same color—hence, the yellow error pile and the blue error pile.

Obviously, all these diagnostic data can be gleaned only if the 100-Hue Test is performed according to Farnsworth's instructions, if, in other words, the four sections are presented separately, one at a time. The 100-Hue Test is not a color confusion test but a color discrimination test. Permitting the candidate to choose from all 85 colors would wipe out this very distinctive feature of it.

Only for the sake of completeness is it necessary to add a few lines about yellow-and-blue color defects. Such defects are of interest to the physician dealing with ophthalmic pathology, since they occur with considerable frequency in diseases of the retina. In the present context, they are of minor interest. It would certainly be unjustified to analyze either the two probably existing subtypes - called tetartanopia and tritanopia - or the trichromatic and the dichromatic varieties. Suffice it to say that, in the dichromatic varieties of this defect, two neutral areas

are to be expected in the spectrum—in what to the normal are the yellow and blue regions of it. In the chromaticity diagrams the main confusion line runs from the essentially yellow to the essentially blue region of the spectrum ogive (Fig. 14). One would also expect two areas of maximum wavelength sensitivity coincident with these neutral areas. Incoming redness in one direction, incoming greenness in the other direction should easily be differentiated from the grey of these neutral regions. One can predict how these two aspects of the yellow-and-blue defect are going to manifest themselves in Farnsworth's tests. In the Panel D-15 Test, yellowish and bluish chips are going to be juxtaposed, proving that the yellowishness and the bluishness of these samples remain unappreciated. In the 100-Hue Test, discrimination will be good in these same regions. To these defectives, it will be in the monotonous red and green quadrants of the color circle where errors will pile up into a "red error peak" and a "green error peak." A sample (Fig. 17) should give some idea of the appearance of such scores.

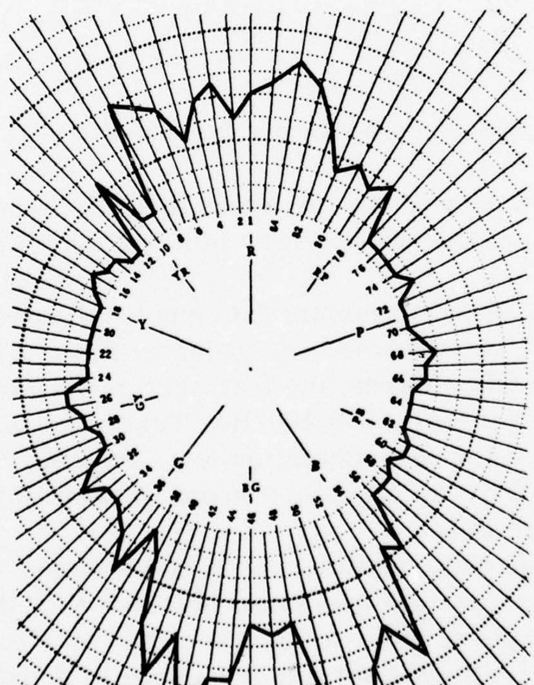


FIG. 17. Score of yellow-and-green defective subject with 100-hue test.

REFERENCES

Chapanis, A. Spectral saturation and its relation to color vision defects. J. exper. Psychol., 1944, 34, 24.

Dimmick, F. L., & Hubbard, M. R. The spectral location of psychologically unique yellow, green and blue. Amer. J. Psychol., 1939, 52, 242.

Dimmick, F. L., & Hubbard, M. R. The spectral components of psychologically unique red. Amer. J. Psychol., 1939, 52, 348.

Farnsworth, D. The Farnsworth-Munsell 100-hue and dichotomous tests for color vision. J. opt. Soc. Amer., 1943, 33, 568.

Hering, D. Grundzüge der Lehre vom Lichtsinn. Leipzig, Englemann, 1905.

Hurvich, L. M., & Jameson, D. Perceived color, induction effects, and opponent response mechanisms. J. gen. Physiol., 1960, 43 (Suppl), 63.

Linksz, A. An essay on color vision and clinical color vision tests. New York, N.Y., Grune & Stratton, 1964.

McKeon, W. M., & Wright, W. D. The characteristics of protanomalous vision. Proc. phys. Soc. (London), 1940, 52, 4, 464.

Motokawa, J. Retinal colour responses to microstimulation. Nature, 1951, 167, 729.

Munsell, A. H. Book of color. Baltimore, Hoffman, 1929.

Nelson, J. H. Anomalous trichromatism and its relation to normal trichromatism. Proc. phys. Soc., 1938, 50, 661.

Ostwald, W. Die Farbenlehre. Vol. I. Leipzig, Unesma, 1918.

Pitt, F. H. G. Characteristics of dichromatic vision. H. M. Stat. Off., London: Med. res. Counc. spec. Rep. Ser., 1935, No. 200.

Purdy, D. McL. Spectral hues as a function of intensity. Amer. J. Psychol., 1931, 43, 541.

Rubin, M. L. Spectral hue loci of normal and anomalous trichromates. Amer. J. Ophthal., 1961, 52, 166.

Rushton, W. A. H. Visual figments in man. The Sherrington lectures, VI, Springfield, Ill., Charles C. Thomas, 1962.

Verriest, G. Further studies on acquired deficiency of color discrimination. J. opt. Soc. Amer., 1963, 53, 185.

Verriest, G. Les déficiences acquises de la discrimination chromatique. Mém. l'Acad. roy. Méd. Belgique. II., 1964, IV, (5), 37-327.

Walls, G. L., & Heath, G. G. Neutral points in 138 protanopes and deuteranopes. J. opt. Soc. Amer., 1956, 46, 640.

Walls, G. L., & Mathews, R. W. New means of studying color blindness and normal foveal color vision. Los Angeles, Univer. Calif. Press, 1952. (Publ. Psychol. No. 7)

Wright, W. B. Researches on normal and defective colour vision. St. Louis, Mosby, 1947.

Wright, W. D., & Pitt, F. H. G. Hue discrimination in normal colour vision. Proc. phys. Soc. London, 1934, 46, 459.

LABORATORY MEASUREMENT OF COLOR VISION

F. J. J. Clarke
National Physical Laboratory
England

The population may be divided into two major classes in terms of color vision performance, the "normal" (about 92 per cent of males, and about 99-1/2 per cent of females), and the "abnormal." The latter group are properly termed color-defective observers, for, although they are of many types, they always show a reduced power of color discrimination to some degree, compared to the normals (known properly as normal trichromats). There is only one exception to this general statement: one type of defective, the tritanope, has superior wave length discrimination to the normal trichromat for the violet region of the spectrum, owing to the co-punctal chromaticity of the isochromatic loci on the chromaticity chart lying just outside the violet end of the spectrum locus. The total number of discriminable, color stimuli is always less for the color defectives than the formidable total for the normal trichromat, estimated at ten million by Judd (Judd, 1952).

It must be pointed out that, for the mild forms of protanomaly and deuteranomaly, the main difference from the normal is of kind rather than of degree of deficiency. In this brief survey, only congenital color deficiencies will be considered. The pathological color deficiencies often tend to resemble one of the classes of congenital deficiency, and are, then, often named accordingly, though this can be misleading. However, a proportion of pathological cases exhibit properties which seem to defy systematic classification.

A considerable difficulty presents itself in ranking the population on a single, monotonic scale of "degree of visual fitness" in terms of their color vision. This is because of the differences

of kind as well as of degree, as mentioned before. A tentative scheme, however, is shown in Table 1.

TABLE 1.

Class of Fitness	Type of Observer	
1.	Normal trichromats	
2.		
3.		
4.	Protanomalous	Anomalous trichromats
5.	Deuteranomalous	
6.	Tritanomalous	
7.	Deuteranopes, Tritanopes	Dichromats
8.	Protanopes	
9.	Cone monochromats	
10.	Rod monochromats	

It will be seen that no less than four classes of fitness have been allocated to the anomalous trichromats: this is because they exhibit a wide but continuous gradation of deficiency from "almost normal" to full dichromatism. The color discrimination of the congenital defective is not improved to any major extent by training; the deficiency is innate. However, it should be noted that intelligent color defectives can often learn to name surface colors with surprising accuracy (allowing for their reduced discrimination), due to the use of achromatic clues and experience. The ideal test of color, vision performance would be to determine the total number of discriminable stimuli but it would take too long ever to be a practical test, unfortunately.

The Laboratory Tests

The main differences between clinical and laboratory tests of color vision lie in the complexity of equipment needed (not forgetting the equipment required for fundamental, radiometric calibrations), the complexity of the testing operation, and the competence of the staff required. A laboratory test, such as measuring the color-matching functions, typically involves numerous individual observations over several observing sessions,

followed by extensive calculation of data. Such a test can be carried out only on large numbers of observers at great length and expense.

1. Anomaloscope. This is the simplest and quickest of these tests effectively involving but one color match. The normal, commercial instruments give a red-plus-green to match a yellow stimulus, e.g., the Nagel instrument. This is usually satisfactory for distinguishing normal, protanomalous, deuteranomalous, protanopic, and deuteranopic observers. But the degree of anomaly is not always correlated well with the match, and misclassifications can arise. Some workers (Drs. Farnsworth, Rautian) have tried an anomaloscope giving a green-plus-blue to match a Cyan stimulus, intended for detecting and measuring tritanomaly, but results can be confused by the effects of preretinal absorption.

2. Wave length discrimination. This most fundamental of measurements gives a good picture of the color discrimination round the edge of chromaticity space and, hence, distinguishes degrees of protanomaly, deuteranomaly, and tritanomaly very well indeed. All classes are distinguished, except for deuteranopia and protanopia (which are confused), and a few cases of protanomaly and deuteranomaly, which are also confused. The conditions of view (especially fixation conditions) can influence the results very strongly.

3. Purity discrimination. This test grades anomalous subjects in severity of defect rather well, but does not distinguish protan and deutan types with even reasonable certainty. It requires more complex equipment, and very competent photometric procedures.

4. Chromaticity discrimination. This is near to being the ideal measurement. However, it requires a full spectral colorimeter of some versatility, and a highly expert colorimetric staff to calibrate and to operate it. The observations are long and exacting. No properly complete study of color defectives has ever been made, and only a handful of normals have their characteristics recorded in the literature (Wright, 1941; 1943; MacAdam, 1942).

5. Color-matching properties. This measurement also requires a full spectral colorimeter and an expert staff. The tests require a full two days' work, at least, often more. The information is complete, and gives a reliable classification for all types, though it does not reveal the degree of defect reliably.

6. Relative luminous efficiency. This measurement can be

used only to distinguish protanomalous and protanopic observers from the other types, and rod monochromats from other types. Yet, it requires an expert staff for the radiometric calibration of equipment.

7. Munsell-Farnsworth 100-hue test. In its normal form, this is only a regular, clinical screening test, but it is the only one that distinguishes all classes of color defective, and that can grade in severity of defect. Its weakness is that the hue circle is arbitrarily divided into four separate collections of chips. This means that many possible types of confusion are excluded from the results. Examination of data from defectives (various sources), shows that the shape of the "error-lobes" on the usual radial chart is distorted, in that there is always a dip (suggesting better discrimination) in the regions of 85-1, 21-22, 42-43, 63-64, i.e., at the four artificial group boundaries. Three possible improvements are suggested by this author.

1. All test chips mixed up together, and a correctly graded hue circle displayed on the wall to reduce intelligence effects.

2. All test chips mixed up, and a correct reference circle provided on the desk; the subject has to match up corresponding chips alongside. This tests hue discrimination exclusively, but on a quantitative basis.

3. A double-wheel recording machine, with a test wheel and a reference wheel, each with the 85 selected Munsell hues on its edge, optics to present each in a bipartite field, and with spatial integration over 1/85 of the circle. This can measure hue discrimination very exactly, indeed. This cheap device can give the best possible type of data in a short time and needs only an inexpensive staff deployed on the job.

8. Heterochromatic threshold reduction factor (HTRF). This technique was invented by Boynton as a practical means of utilizing the sophisticated Two-Color Threshold measurement of Stiles. It does not require very elaborate equipment or calibration procedures, and, initially, it looked exceedingly promising. However, further work (unpublished) shows that very misleading results can be obtained from a small proportion of color-defective subjects. At present, this technique should not be considered other than a research procedure.

9. Color-naming. This involves categorizing assorted spectral stimuli with a restricted group of hue names, usually from among red, orange, yellow, green, cyan, blue, violet, or purple. At near threshold, a single name is sufficient, but at higher levels more valuable information if obtained by making the ob-

server give a main and a secondary hue, and applying appropriate treatments to the data (Boynton, Schafer, & Neun, 1964; Boynton & Gordon, 1965). This new technique seems to be reliable, and shows the presence of residual color vision in several cases where conventional tests reveal no discrimination at all.

In conclusion, it is to be emphasized that the state of fixation influences all measurements to some extent, and some measurements very markedly. The use of a slow, flashing technique to control any local adaptation will improve the reproducibility and significance of experimental data.

REFERENCES

Boynton, R. M., & Gordon, J. Bezold-Brucke hue shift measured by color-naming technique. J. opt. Soc. Amer., 1965, 55, 1, 78-86.

Boynton, R. M., Schafer, W., & Neun, M. W. Hue-wavelength relation measured by color-naming method for three retinal locations. Science, 1964, 146, 666-668.

MacAdam, D. L. Visual sensitivities to color differences in daylight. J. opt. Soc. Amer., 1942, 32, 5, 247-274.

Wright, W. D. Sensitivity of the eye to small colour differences. Proc. phys. Soc. London, 1941, 53, 93-112.

Wright, W. D. The graphical representation of small color differences. J. opt. Soc. Amer., 1943, 33, 11, 632-636.

DISTANCE VISION
Olin Smith, Chairman

DISTANCE VISION
(BINOCULAR DEPTH PERCEPTION)

R. L. Vasa
Head, Optometry Branch, Bureau of Medicine and Surgery
U.S. Navy Department

"Binocular depth perception is not a simple visual function" (Enoksson, 1964). The accuracy in localizing an object at the correct distance is dependent on learning to interpret cues, some of which are quite indirect and quite complicated. While it is assumed that most forms of depth perception involve the interpretation of cues, there is some difference of opinion as to whether stereopsis can be described as a form of depth perception which makes use of retinal disparity as a cue.

The visual factors which contribute to the perception of distance can be outlined as (a) monocular or binocular, (b) visual factors which depend on the stimulation of the retina, and (c) adjustment factors, such as accommodation and convergence. In regard to the visual monocular factors, under the broad heading of geometric perspective may be included overlay, association with other objects, vertical position in the field, apparent foreshortening, size of known objects, apparent convergence of spacing of parallel lines, monocular parallax with a single object, or with more than one object. The contributions of each of the foregoing to depth perception provide the one-eyed individual with a considerable armamentarium for making depth judgments. A second monocular category is "aerial perspective," a form of depth perception which makes use of the effect of the atmosphere on the appearance of an object as a cue for distance. A third monocular factor is the distribution of light and shade, such as the shading which gives the impression of a solid sphere rather than a flat disk. Highlights or specular reflections can be cues for solidity. Shadows of objects also serve as cues for the position of objects in three-dimensional space (Fry, n.d., Ogle, 1956).

When binocular visual factors in the perception of depth are considered one may include stereopsis (retinal disparity), binocular relief, binocular differences in perspective and visibility, separation of diplopic images.

The term stereopsis frequently is used to designate any form of visual perception of the third dimension. In this instance, it is used to designate the use of retinal disparity as a cue for the perception of the third dimension. This is, by far, the most important of all the cues of the third dimension, especially for objects at near and intermediate distances (Fry, n.d., Ogle, 1956).

Binocular relief is not encountered in the ordinary use of the eyes. As to binocular differences in perspective and visibility, Dr. Ogle lists as one of the binocular visual factors the gross dissimilarities in the perspective patterns presented to the two eyes by a small object lying close to the eyes. In regard to the separation of diplopic images, Dr. Ogle notes that the perceived separation of the two members of the diplopic image of an object may serve as a cue to depth (Fry, n.d.; Ogle, 1956).

The adjustment factors in the perception of depth include accommodation and convergence. However, "there is no decisive evidence that changes in accommodation or proprioceptive impulses during convergence play any decisive role in stereoscopic vision." This is not to say that these two factors do not enter into the discrimination of distance, since the two functions are interrelated as determined by the A.C.A. ratio. Dr. Enoksson found a correlation between binocular rivalry and stereoscopic acuity, the depth acuity being better when the alternation in rivalry is rapid (Enoksson, 1964).

Dr. Hofstetter notes that the clinical tests of stereopsis differ from the stereopsis tests used in surveys and screening projects. In clinical testing, the practitioner attempts to establish the presence or degree of binocular vision and usually does not pursue the degree of stereopsis, as long as an appreciable amount is demonstrated (Hofstetter, 1956; 1962). To this end, the refractionist uses a battery of clinical tests to determine the fusional amplitude and accommodative amplitude, as well as the relationship between accommodation and convergence under various conditions. The prism-convergence and prism-divergence measurements indicate the range within which the individual can maintain single binocular vision. The degree of stereopsis attained during the progress of these tests is not known. These tests are administered for both distant and near vision.

A recent development in refraction techniques is "stereo-

refraction." A stereo projector, or a projector with a vectograph slide, is used to provide targets which are plane-polarized in meridians at right angles to each other. The phoropter is equipped with polaroid filters so arranged that the right eye sees one of the projected images, the left eye, the other image. The projector may be equipped to provide variability in the separation of the two images, increasing or decreasing the difficulty of the task of the observer to fuse, or to perceive depth. While this technique is not used to provide a scaled measure of depth perception, such measures may be calculated for the various targets. With this technique, it is relatively simple to demonstrate the presence or absence of aniseikonia and/or cyclophoria, factors which contribute to distortion of the objects in the field of vision.

One of the most convenient devices for determining the presence or absence of stereopsis is the DiaStereo (Pardon, 1962). It consists of a plastic disc which fits on the end of a flashlight. Embedded in the disc are three black dots, one of which is displaced forward of the other. The disparity is of the order of about 84 per cent on the Shepard-Fry scale. The background provides a uniform field. The observer is asked to identify which of the three dots seems to stand out from the rest. The flashlight may be held in any one of a number of positions. The test administrator always knows which dot is forward of the others. A correct response indicates that the observer has at least 84 per cent stereopsis. Indications are that those individuals who make a correct response are then able to pass any of the other stereo tests, including the Ortho-Rater.

A simple, clinical method of determining the presence or absence of binocularity is the Worth four-dot test. A projector with the proper slide is used to provide a target consisting of four dots arranged in a diamond shape. The uppermost dot is red, the two side dots are green, and the lower dot is white. The observer is equipped with red-green glasses: red before one eye, green before the other eye. If he is fusing, the observer will see four dots in the shape of a diamond; the lower dot may be either red or green, and may alternate. If fusion is not present, five dots will be reported in the event diplopia is experienced, or, when one eye is suppressed, either three dots or two dots will be reported.

The tests for stereopsis used in surveys or for screening purposes are made with especially fixed and predetermined amounts of convergence and accommodation stimulus. If these

AD-A062 145 ARMED FORCES-NRC COMMITTEE ON VISION WASHINGTON D C F/G 6/16

THE MEASUREMENT OF VISUAL FUNCTION PROCEEDINGS OF SPRING SYMPOS--ETC(U)

1968 M A WHITCOMB, W BENSON NONR-2300(05)

UNCLASSIFIED NL

2 OF 3

AD
A062145

AD
A062145


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

stimulus values do not permit single binocular vision, the examinee fails the stereopsis test, whereas he may show normal stereopsis under more favorable clinical conditions (Hofstetter, 1956; 1962).

Dr. Tiffin reported an apparent relationship between age and scores obtained on the Ortho-Rater stereopsis test, suggesting a slight increase in stereopsis up to age 35, and a continuous drop after age 50. Dr. Hofstetter notes that other investigations of stereopsis have not shown this, and that the scores obtained depend on factors other than stereopsis. Drs. Fry and Kent investigated the relationship between stereopsis and blurredness, and showed that stereopsis decreased rapidly with increases in blur (Hofstetter, 1956; 1962).

The determination of the presence or absence of depth discrimination by U.S. government agencies is used for a variety of purposes. The U.S. Navy employs the Verhoeff Stereopter for qualification of naval aviators and candidates for flight training. Qualification consists of correct answers for each of the eight positions of the rods. Three separate runs may be made with the apparatus held at a distance of one meter from the examinee, who must report eight out of eight correctly in two of the three trials. Dr. Trumbull (1951) reported that the coefficients of reliability for the Verhoeff for four different scoring methods were .79, 181, 82, and 82, figures which compared favorably with reported findings on the B & L Ortho-Rater of .83, and for the Keystone Telebinocular of .80. One study of the Howard-Dolman gave coefficients of reliability varying from .69 to .78, depending on the settings used—behind, in front, etc. The U.S. Army requires that aviators pass the Verhoeff test, i.e., no errors, when used in lieu of the U.S. Air Force Vision Tester. Both Army and Air Force require that the applicant makes no error in lines B, C, or D when using the AF Vision Tester (Machine). The Air Force also uses the Verhoeff with the same requirement as above—no error in any trial. In addition, the Air Force provides a third alternative, the Howard-Dolman test, in which the average error must not exceed 30 mm.

The stereopsis test in the AF Vision Tester is rated from 57.7 per cent to 100 per cent stereopsis on the Shepard-Fry scale. This could lend itself to scaling for determining the level of stereopsis in each case, thereby providing a numerical value for possible automatic recording.

REFERENCES

Enoksson, P. Binocular rivalry and stereoscopic acuity Acta Ophthal., 1964. 42, 165-178.

Fry, G. A. Mimeo notes physiological optics, Chap. X and XI. Ohio State Univer. School Optom., n.d., 615.

Fry, G. A. Mimeo notes, Physiological Optics, Chap. XII. Ohio State Univer., n.d., 3.

Hofstetter, H. W. Industrial vision. P. 74-79, Chilton Co. 1956 J. Amer. Optom. Assoc., 1962, 33, 7, 510-512.

Ogle, K. N. Research in binocular vision. Philadelphia: Saunders 1956. Pp. 133-141.

Pardon, H. A new testing device for stereopsis. J. Amer. Optom. Assoc., 1962, 33, No. 7, p. 510-512.

Trumbull, R. Reliability of the Verhoeff test of depth perception. J. Psych., 1951, 32, 35-41.

SOME DISTINCTIONS BETWEEN PERCEIVED DEPTH AND DISTANCE[1]

Olin W. Smith
Cornell University

The report of Working Group 20 of the Armed Forces-NRC Committee on Vision by Drs. Jampolsky and Morris (1964) includes distance judgments as one of the visual parameters for which grades of visual fitness should be established for pilots. A logical extension of the task of Working Group 20 would be a discussion of standard laboratory tests of perceived distance, the natural assumption being that any one of several laboratory tests of perceived distance could prove to be useful as a screening device.

The above strategy for the solution of practical problems has been so successful that the path from laboratory to field has been worn bare. Of the eleven parameters listed by Drs. Jampolsky and Morris (1964), however, distance judgments will probably be the exception. The reasons are numerous. One is that there are, at present, no standardized laboratory procedures or tests for perceived or judged distances. Standardization implies only that generally agreed-upon procedures are employed in the administration of a test and that norms of performance for some population have been established. A second is the assumption, implicit in the strategy, that some laboratory test of perceived distance will prove to have predictive validity of field perceptions of distance in general. This means, other things being equal, that the perception or judgment of distance is independent of the requirements of the task. This paper attempts to prove that assumption to be false. A third and most important reason

1. This paper was supported in part by PHS Grant No. B-1586 to Cornell University.

is that no general agreement in the literature exists for distinguishing between the data and the theory of perceived depths and the data and the theory of perceived distance.

A basis for distinguishing between perceptions or judgments of depth and distance are proposed (Gogel, 1964), as well as three subclasses of distance judgments coincident with the distinction between depth and distance. The theory of perceived depth is demonstrated to be inadequate as the theory of distance. In addition, phylogenetic evidence is cited to demonstrate a hierarchy of behaviors, the lowest being indicative of visual direction, the next being perceptions of depth, and the highest being judgments of distance.

Most students of perception have been content to work in the laboratory and have exhibited little interest in clinical practice. By clinical practice is meant the application of laboratory techniques, theory, and data to field problems. Consequently, the literature is, for the most part, a literature of the traditional problems of the laboratory. In this literature, the theory of depth has been accepted as the theory of distance, and vice versa. Therefore, measures of perceived depth have been frequently accepted as measures of perceived distance.

Perceptions of depth and distance differ in a number of ways, and perhaps the easiest way of describing these differences is by examples. A relatively uncomplicated instance of a perceived depth is that of a single light or spot in an otherwise dark field. When viewed monocularly, the location of the light or object is perceived as being merely "out there." In this sense, a perceived depth is involved. Perceived distance of the light or object is not a necessary condition for perceiving a depth. The proof is that observers are incapable of judging the true distance of the light or object in terms of some physical unit, such as a foot, or a yard. Ordinarily, a perceived distance is a perceived depth that is scalable in terms of physical units such as feet, yards, stopping distance of a car, "jumpable" distance, or landing distance of a plane. A number of different types of physical units exist. Therefore, the above definition of perceived distance requires further qualification.

Take, for example, a linear, perspective line-drawing of a tunnel in which a box is portrayed as resting on the floor. Judgments of which points on the floor are nearer or further away than the box can be obtained with no difficulty. Similarly, fractionation judgments can be easily obtained. Both types of judgments can be accurate under conditions in which observers are

incapable of estimating the physical magnitudes of the portrayed space. Consequently, these types of judgments are evidence of perceived depth, rather than distance.

Depth and distance judgments do not necessarily differ according to the type of scale used. For example, judgments of "nearer" or "farther," and bisections can lead to ordinal and ratio scales, respectively, without involving true, distance judgments. From this it may be concluded that the type of scale, be it nominal, ordinal, interval, or ratio, is not the basis for determining whether any one set of judgments is evidence of perceived depth or distance.

The method of reproduction under everyday-life conditions can pose problems for any definition of perceived distance. Three examples may serve to clarify further the distinction between perceived depth and distance. These examples involve assumptions about the process, or how judgments are made.

Consider the task of having an observer adjust a marker so that it appears to be at a distance equal to that of the standard. Assume the visual angle of horizontal separation of standard and variable to be 1°. The observer causes the standard and variable to appear equal in distance. This is a depth judgment, since discriminations of merely nearer or further can account for the judgment of equality. These discriminations do not require judgments of the distance of either standard or variable in terms of physical units, such as a foot, or a yard.

A second instance or reproduction is that in which the observer reproduces the apparent distance of a standard object. In this case, assume the angular separation of standard and variable to be 180°. This type of judgment is evidence only of a depth perception, since the apparent depth of the standard can be reproduced in terms of the apparent depth of the variable. No estimates are required in terms of physical units for the judgment of equality of apparent depths.

A third instance of reproduction is illustrative of the transition from perceived depth to perceived distance. In this case, the observer is given corrected practice in reproducing a perceived depth. With sufficient practice the perceived depth of the standard can be reproduced accurately. These reproductions constitute scalar units for the measurement of extents much greater than that of the distance of the standard during training. In this case, the observer need not know the physical dimensions of the unit, prior to its successful use, for scaling depths in terms of a physical unit. The successful scaling of any perceived depth

in terms of physical units sufficient for perceived distance involves distance constancy, since equal units of physical distance at different distances from the observer subtend different visual angles.

An apparent exception to the requirement of distance constancy is learning to identify a specific distance. This is, however, really only a nominal judgment. Suppose that the distance from an observer to an object has been measured, and the observer has been told that object is at 30 yd from his position. The observer learns that the apparent depth of object x is to be named "30 yd." As a consequence of this learning, he is also able to judge other objects in other fields of view as being at an apparent depth equal to that of object x. This type of judgment should also be classified as a depth judgment. The reason is that the apparent depth of object x from the observer is the unit. The unit could have been labelled A, B, C, or D with the same results as the designation of 30 yd. Consequently, the label of the unit is of no material importance for classifying a judgment as evidence of perceived depth versus distance. The important distinction is that of process. The assumption here is that judgments of distance require processes of scaling in addition to those required for perceived depth. Phylogenetically, this assumption is believed by the author to be correct and evidence will be exhibited to support it.

Visual direction, depth, and distance can be concomitant perceptions for the human adult as well as for other primates. The simplest or most primitive of the three, however, is visual direction. Reflex motor responses to light are common in phototropic insects. No evidence indicates that these insects experience depth or distance in the usual sense of the words.

Many fish are likewise phototropic, but demonstrate also that they perceive depth as well as visual direction. Fish, such as the pike or Pacific salmon, give clear evidence of ordinal judgments of depth. That is, they can discriminate visually between overtaking or being left behind.

The Pacific salmon is of special interest. It perceives vertical depths, and will leap at barriers beyond its physical capacity to mount. This act indicates that the salmon is very inaccurate in scaling perceived depths in terms of leaps or jumps. The discrimination of the existence of a barrier may be sufficient for an attempt to jump or leap it. In this sense, the perception is indicative of a nominal scale, the presence of a vertical depth but not of scaled distance. Evidence required of the salmon for

perceived distance would be leaps graded in magnitude for the perceived heights of barriers. Since this evidence is not well established, most imperfect, if any, perceptions of distance by the salmon may be assumed. Consequently, perceived distance, as defined here, probably occurs only in higher organisms.

Porpoises, many land-based mammals, and the primates provide excellent evidence of perceived distance by their motor acts. For this reason, three types of physical units are proposed for the scaling of depths in distance terms.

Class I is composed of motor acts such as a step, jump, or arm's length. These units are measurable but still private to the perceiving animal. As units they are less precisely defined than units, such as a centimeter. As a unit, the motor act is the most primitive, since it is applicable to the widest range of species.

Class II is composed of units that are defined by objects controlled by some animal. In all instances, the objects serve as extensions of the behavioral capacities of the animal. Two subsets are proposed. The first comprises the physical dimensions of objects, such as planes and automobiles. The physical sizes of these objects are precise physical units by which depths can be scaled.

The second subset is composed of the performance capabilities of objects controlled by the perceiver: a good example of this subset is the comparison of a V. W. and a Ferrari in terms of their capacities for acceleration. Other things being equal, a Ferrari can overtake and pass another auto successfully when a V.W. cannot. In either case, the unit of judgment is not precise. But, in either case, the performance characteristics of the vehicle provide a known unit of judgment.

Class III is composed of arbitrary units of precise physical values. Examples are feet, meters, and depth-extents that can be measured precisely, but need be identified by the perceiver only as units. Most instances in the literature in which these units have been used have involved human observers.

This little classification system can be very useful for a number of reasons. First of all, it suggests that different processes of perception or judgment are required for scaling depths in the different types of distance units. Phylogenetically, this seems to be the case. The developmental literature of humans most definitely reveals an order of maturation parallel to the three classes. For instance, visual direction and depth can be demonstrated early in life, while the earliest evidence of per-

ceived distance is given by motor acts. Successful scaling in units of a foot or of a yard is a fairly difficult task. The lowest age of accomplishment has not been well established, but ten- and eleven-year-old children can experience difficulty.

The classification system also is evidence of why the theory of depth cannot possibly be the complete theory of distance. In a quantitative sense, measures of distance will always contain sources of variance foreign or extraneous to measures of depth.

Another line of evidence confirms this. Spatial tasks involving perceptions of depth and distance have been investigated extensively by psychometrists. They have used theories and methods radically different from those of traditional perception to predict how well individuals and groups can learn to perform spatial tasks. Their theories have been, for the most part, the theories of measurement, analysis, aptitudes, and test construction. Traditional theory of depth has been of but limited or no utility in the prediction of performance on these spatial tasks. Psychometric success in predicting spatial performances is clear evidence that substantial components of many spatial tasks are independent of perceived depth.

The successful, scientific clinician of perceived distance must necessarily be task-oriented. The degree to which he may be successful will depend to a large extent on how well he can make job analyses of the tasks for which his clinical advice is sought. The classification system can be useful in this respect, and can serve as a guide for determining whether some act is dependent on depth perceptions, or distance judgments.

For instance, the tasks of driving and flying have been repeatedly analyzed. Repeatedly, these tasks have been asserted to require accurate judgments of distance. When this classification system, however, is used to analyze landings and take-offs of both light and heavy land-based planes, the analyses reveal that perceptions of distance are not necessary for the successful performance of either task. This does not mean that judgments of distance cannot be necessary at times. Whether they are or not depends on the conditions, and how the tasks are performed. The analyses do reveal, however, that perceptions of visual direction and depth can be sufficient for the successful performance of both tasks.

A similar analysis was made of many components of the task of driving. Here again, perceptions of visual direction and depths can be sufficient. In fact, many of the components of driving require relatively low-level perceptual abilities. A rather humor-

ous bit of evidence confirming this was the arrest of a monkey in Florida for driving without a license. The monkey was accompanied by his owner, of course, but still the monkey demonstrated adequate tracking skills in guidance. In driving, however, perceptions of distance may also be necessary at times.

Theories of distance will necessarily be oriented, if they are to be effective, to the relevant classes of judgments. Moreover, there is no rational basis for expecting the theory and data of one class to account for, or to predict performance on other classes of judgments. If true, this means that the laboratory, in the traditional sense of the word, will not be able to provide the clinician with any test of distance perception that can be expected to have uniform and general predictive validity.

The units of the three classes of perceived distance must be *learned* before they can be applied. Some units, such as yards, can be learned readily by human adults, while less precise units, such as the performance capabilities of planes, may take several months to learn.

The performance characteristics of planes, in general, vary greatly and determine the depths and possible distances that need to be perceived for successful operation. Because of this, the grades of visual fitness that were suggested by Drs. Jampolsky and Morris (1964) should be oriented toward the requirements for the successful operation of different classes of planes, rather than planes in general.

The above point can be illustrated readily. Assume a 12,000 ft runway with heavy and light planes having "no brakes" braking distances of 8,000 and of 2,000 ft respectively. The heavy plane can be touched down within a range of 4,000 ft for a successful "no brakes" landing, while the light plane has a range of 10,000 ft. Assuming standard deviations as indices of accuracy of visual fitness, the pilot of the light plane can be as much as 250 per cent less accurate than the pilot of the heavy plane in accomplishing a successful landing.

Some depth discriminations involved in flying are probably as specific and task-determined as are distance judgments. For instance, the nature of the learned discriminations that are necessary for pilots of heavy, carrier-based planes is decidedly more exacting than those of pilots of equivalent, land-based planes. This suggests the possibility of differential standards for pilots of equivalent classes of planes dependent on whether the planes will be based on land or on carriers.

In conclusion, the visual parameter of judged distance that

was suggested by Drs. Jampolsky and Morris (1964) should be subdivided into measures of depth and measures of distance, both of which involve substantial learning components. So as to be useful in establishing visual requirements for flying, the measures should be based on the types of discriminations and judgments imposed on pilots by the various classes of planes in use.

REFERENCES

Gogel, W. C. Size cue to visually perceived distance. Psychol. Bull., 1964, 62, 217-235.

Jampolsky, A., & Morris, Ailene. Visual requirements for flying: some aspects of re-evaluation. Washington: Armed Forces-NRC Comm. on Vision, Rep. of Working Group 20, 1964.

PHORIA AND
OCULAR ROTATION
Kenneth Ogle, Chairman

HETEROPHORIA AND OCULAR ROTATIONS
or
BINOCULAR COORDINATION

Arthur Jampolsky
Institute of Visual Sciences, Presbyterian Medical Center
San Francisco

The test objectives are to determine (a) if the eyes work together, and (b) how well the two eyes work together, i.e., whether they will continue to do so under normal, dynamic, and stress conditions.

It is the binocular-coordination capability that is to be determined. The term heterophoria, by definition, is limiting. The term binocular coordination defines assessment of any degree or type of latent or manifest deviation, and gradations of security of fusion-lock.

The assessment of this visual capability traditionally requires many judgmental values in the assessment because of the many variables inherent in the testing procedures and interpretation.

1. Whether there is fusion present or not is determined by both sensory and motor tests. Fusion is here defined as the presence of bifoveal (full) fusion for the primary positions. There are several sensory tests by which one may subjectively determine the presence or absence of bifoveal fusion. The determination, by tests of the motor apparatus, that there is no latent or manifest deviation for the primary position implies that there is bifoveal fusion.

2. How well the eyes work together may be determined by tests to detect both sensory and motor defects, and by tests which impose both sensory and motor stresses upon the security of the fusion-lock.

a. Motor defects, which must be overcome by the fusion apparatus, consist of any latent deviation in the primary position, or any oculorotary defect which may produce a difference in deviation in some other non-primary positions.

b. Sensory defects, such as suppression or inhibition of a region (usually macular) of the binocular field, may exist with good "fusion," adequate fusion amplitudes, and little or no motor (deviation) defect.

c. Motor and sensory stresses upon the fusion-lock are provocative tests to assess the security of the fusion-lock. The usual motor stress is the imposition of prisms during fusion whereby fusion-vergence innervation is required to overcome the prism-induced stress. The so-called "recovery point" of the fusion amplitude is the most reliable. The sensory stress of the fusion-lock is the degradation of fusionable contour by diminishing contrasts, or otherwise blurring the image of one eye relative to its fellow. Specific tests are discussed later.

There are certain problems relative to the determination of binocular cooperation which are unique to the assessment of this particular visual parameter. Here, precisely what the basic deviation consists of, that one seeks to detect, is often a problem of disagreement. For this presentation, it will be assumed that the basic deviation (motor misalignment) is that deviation which the fusional-vergence innervation must overcome to keep the deviation latent. This fusion-free position is the deviation remaining when fusion is maximally disrupted, with all of the other tonic influences remaining during the testing of an alert, attentive subject under the habitual, everyday-seeing situation. The fusion-free position definition usually implies an emmetropic state, or refractive-error correction in place. For testing purposes relative to this symposium, it will be assumed that the habitual situations, with or without customary correcting lenses, are used during the test.

The causes of the variability in the testing procedures and interpretation are discussed in four parts: 1. the target; 2. the test environment; 3. the subject; and 4. the examiner.

1. The target size, shape, color, contour boldness, and accommodative stimulus, all are of importance in the test determination and must be specified.

2. The environment factors of illumination level, peripheral fusional contours, empty fields, the natural situation versus utilization of red-green lenses, and extraneous light sources are of importance.

3. The subject's head position, attention status, attitude relative to the desire to do well or poorly affect the test determination.

4. The examiner's interpretation and habit patterns, rapidity of test determination, etc., similarly affect the test results.

It is not surprising, therefore, that testing procedures for heterophoria and ocular rotations have been specified in detail, the equipment listed, and manuals prepared. The presence of the above four classes of many variables have usually necessitated judgmentally derived decisions in assessing this visual capability after the test determination has been completed.

A machine-testing device, such as the Armed Forces Vision Tester, standardizes some of these variables by better head fixation, and standardization of the test targets and the visual environment.

Another historical problem in the assessment of this visual parameter has been the failure to detect small angles of frank esotropia (manifest deviation) with a sensory adaptation of anomalous correspondence, and the failure to detect certain congenital rotation restrictions such as Duane's and Brown's syndromes, or intermittent exotropia.

Culver, in a critical re-evaluation, found 22 instances of heterotropia in trained pilots. No value judgments are here implied, but it should be noted that such diagnoses should and can be detected during an adequate and simple screening procedure.

Brown's and Duane's syndromes are often missed because the subjects exhibit perfect motor and sensory fusion in the primary positions. Very marked restrictions of rotation in non-primary positions may be easily overlooked during a cursory examination of ocular rotation if the subject's head is not fixed during the maneuver.

Subjects with intermittent exotropia similarly may exhibit perfect motor and sensory fusion for the primary and even non-primary positions, the deviation becoming manifest only in a situation with a poverty of peripheral, fusionable contours, such as a "blank-sky" background, or during night driving, etc.

Now to return to the test objectives and specific testing procedures. It is clear that the objectives are to determine

1. the presence or absence of a full fusion-lock under habitual conditions for distance and for near fixation (40 cm), and

2. how secure is the fusion-lock in the primary and other positions of gaze.

Clinical tests and laboratory tests do not materially differ in assessing this visual function.

Both subjective and objective tests are used for this assessment, the former requiring the subject's response relative to his visual percept (applied psychophysics). The latter usually involves the examiner's observation of the subject's eyes for detection of the deviation or rotatory disability.

What is not commonly appreciated is the fact that objective tests may be employed to determine both fusion status (ordinarily, subjectively determined), and the motor defects.

1. Subjective tests for the fusion status seek to determine the presence or absence of foveal suppression. The presence of 100 per cent stereopsis implies bifoveal fusion, but it must be recognized that "perfect" sensory and motor fusion may occur, with good fusion amplitudes and stress tolerance, without the percept of stereopsis.

Subjective tests which determine that there is no deviation in the primary positions are commonly utilized, and it is implied that there is a fusion-lock.

The ideal test criteria for this subjective test requires maximal dissociation (fusion disruption). Maximally dissipating the fusion innervation results in the determination of the defined, basic deviation, whether it be latent or manifest.

The testing method usually employed dissipates fusion only in a relative manner by creating a dissimilarity between the images falling on the two retinas. The Maddox rod, or red glass, either changes the shape of the observed spotlight target into a streak image, or changes the color of one spot. Alternatively, a vertically placed prism before one eye, in an amount to exceed the vertical fusion amplitude, creates diplopia, and the deviation is determined by a graduated, horizontal prism to align the diplopic spot vertically.

The subjective test to determine the deviation for near fixation (40 cm) should be of the same construction as the subjective test used for distance fixation. Often this is not the case, and a different test is used for near than is used at the distance, with the expected addition of variables.

The Thorington test at near fixation is a suitably performed Maddox rod test with good accommodative control, and consists of a small back-lighted pinhole in the center of a card held by the subject. The Maddox rod before one eye of the subject gives the percept of a line which is localized by means of a horizontal or vertical row of print centered around the pinhole. Alternatively, the prism-dissociation method, or a Maddox Wing test,

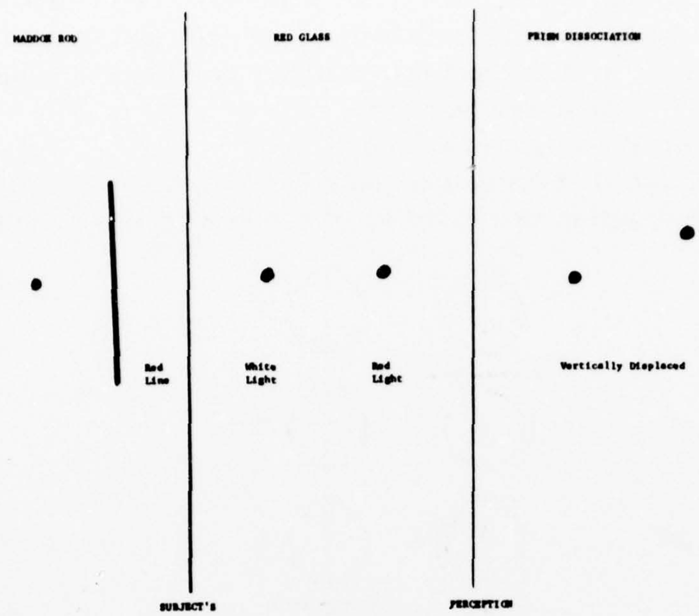


FIG. 1. Diagrammatic representation of subject's percept during following tests for basic deviation (left to right): Maddox rod, red-glass test, and prism-dissociation methods.

is sometimes used with different accommodative stimulus control, and even a different testing distance (Maddox Wing at 33 cm).

The principal criticism of the above-described subjective tests is that there is incomplete dissociation, and insufficient dissipation of the fusion innervation, since each retina receives an image, although differing in size, shape, or color. Often, there is a learned zero point, and non-naive subjects frequently know well how to describe a "perfection" endpoint or orthophoria. The examiner is at the mercy of the subjective response. In addition, the target design and environmental, visual surround are usually encountered variables.

These same subjective tests when used for detection of oculorotatory defects should employ a fixed head position. As usually performed, the head is not fixed, and thus the subject may make small but significant head movements in order to report either little or marked difference in the nonprimary positions of rotation, depending often on his desire to pass the test or exaggerate a defect.

2. Objective tests for the fusion status such as the cover test are preferable in that they require only that the subject fix a target and that the observer detect eye positions and movements.

With these simple ingredients, it is possible to determine very adequately the fusion status as well as the type and degree of deviation in the primary and non-primary positions of gaze.

Criteria for the cover test are:

1. central fixation in each eye
2. a method of occlusion control of either eye
3. observation or recording of eye movements or positions.

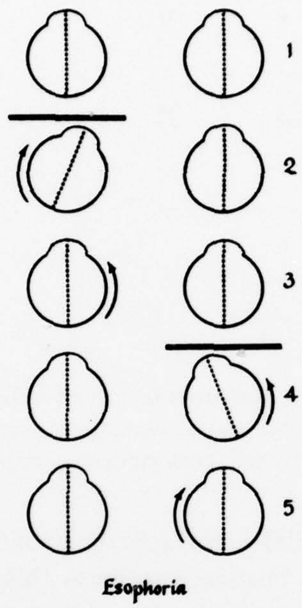


FIG. 2. Cover test in esophoria.

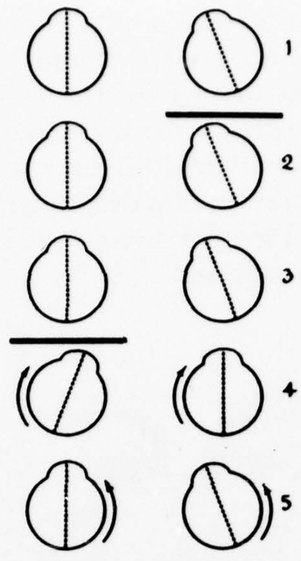
1. No obvious latent deviation.

2. Cover left eye; no movement right eye, which was, therefore, foveally fixing under binocular conditions. Slow adduction of covered eye may be noted as fusion innervation subsides following disruption of fusion by cover as eyes assume basic deviation position or relative convergence.

3. Removal of cover; no movement of right eye as it continues to fix foveally. Abduction of uncovered left eye occurs as fusion realigns visual axes in parallelism and fusion lock. Possible oscillatory movements of both eyes as fusion lock is regained because of diplopia observed immediately upon removal of cover. Type of movements observed depends on which image is being observed before refusion occurs.

4. Cover right eye; no movement of left eye. Therefore, there was also foveal fixation of left eye under binocular conditions. Since foveal fixation of right eye (2) and foveal fixation of left eye (4) are found to exist where binocular conditions are present, manifest tropia is ruled out. Slow adduction of covered eye may be noted as in (2).

5. Removal of cover produces results same as in (3). Cover-uncover test in this circumstance rules out a tropia. Type of phoria is determined by direction of movement of covered eye. Same explanatory notes exist for exophoria with exception that covered eye abducts.



Monocular Right Esotropia

FIG. 3. Cover test in monocular, right esotropia.
1. Manifest deviation of right eye may be observable.
2. Cover right eye, no eye movements; therefore, left eye was foveally fixing under binocular conditions. No eye movement of covered eye since eyes are already in position of basic deviation.
3. Removal of cover, no eye movements. Therefore, persistent, constant esotropia exists, with no fusional attempts.
4. Cover left eye, version movement (parallel movement of both eyes) to right, for right eye to assume foveal fixation. Therefore, right eye under binocular conditions was in adduction, and abducted to fix foveally. This parallel movement to fix carried covered left eye with it.
5. Uncover left eye; version movement to left in order for dominant left eye to assume habitual foveal fixation, carrying right eye with it to its usual esotropia basic position. In this instance, left dominant eye is habitually used in fixation, although it has been demonstrated that right eye is capable of fixing, but not maintaining fixation under competition of binocular situation. Same explanatory notes apply to constant, monocular exotropia, but with opposite movements.

The advantages of the objectively performed cover test are:

1. maximum dissociation, i.e., one or the other eye completely occluded

2. A qualitative and quantitative determination of the deviation

3. good sensitivity, i.e., one-to two-prism diopters of observation, with more sensitivity for recording techniques

4. easily performed in the primary, or any non-primary position or circumstance (habitual or otherwise).

Another objective test for the fusion status (presence or absence of bifoveal fusion-lock) is the prism, eye-movement test. This objective test of a sensory (usually subjectively determined) defect of foveal suppression can be done in any eye position or circumstance. The subject merely fixes a small light source with both eyes open. A four-prism dioper prism is introduced base-out before one and then the other eye, and the eye movements are observed or recorded.

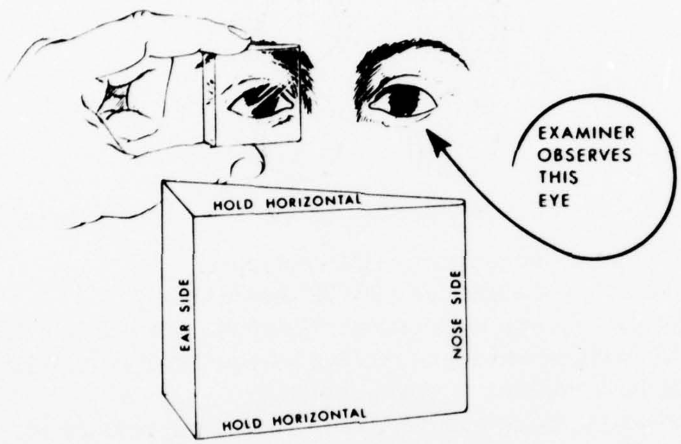


FIG. 4. Prism-binocular, eye-movement strabismus test. Prism is so marked as to obviate any confusion relative to correct positioning before either eye. Examiner especially notes movement of eye without prism, when prism is placed before fellow eye, and again when it is removed. Test is then repeated by introducing and removing prism before each eye in turn.

If the observed left eye of the subject (Figs. 4 & 5) is not participating in binocular foveal fusion, i.e., is foveally "blind" or inhibited, there will be a conjugate movement of the eyes if the prism is introduced before the fixing right eye. It is this conjugate movement of both eyes which conveys the information that as the foveally fixing right eye moves to fix the prism-displaced image, the left eye is carried along as "excess baggage," and the image movement in the left eye over the inhibited macular area is unappreciated and elicits no compensatory eye movement. Further, when the prism is placed before the left eye, the image shift over the inhibited or suppressed area is unnoticed and elicits no shift in fixation of that eye, i.e., that is no

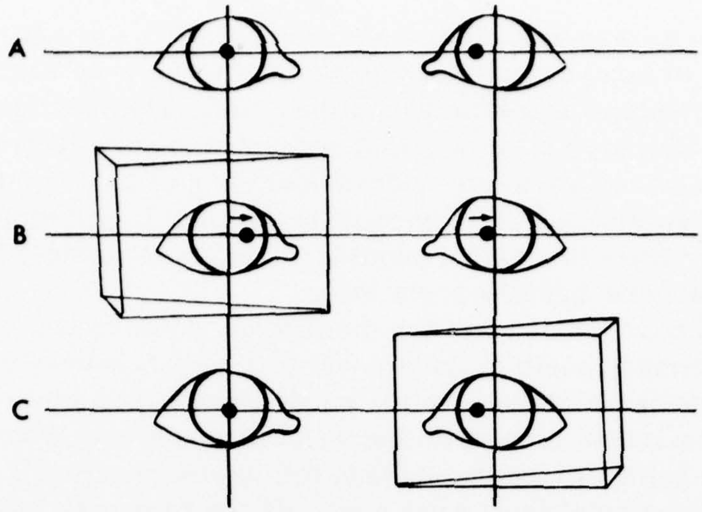


FIG. 5. Prism-binocular eye-movement strabismus test. A represents convergent strabismus of left eye under usual circumstances. B shows patient's left eye move and stay moved as prism is placed before good, fixing right eye, indicating left eye strabismus in this case (esotropia). When prism is removed from right eye, left eye is observed to move back to its original position (nasalward). Positive test for strabismus exists when observed eye (without prism) is seen to move and stay moved when prism is introduced, and is seen to return and stay returned when prism is removed. Actually, more careful observation of both eyes will reveal a version (conjugate movement of both eyes when prism is introduced, and again when prism is removed, in circumstances where positive test exists). C when prism is placed before strabismic eye, observed right eye does not move.

eye movement of either eye. Thus, either "no" eye movement, when the prism is placed before one eye, or a conjugate eye movement when the prism is placed before the fellow eye, adequately determines the presence of foveal mascular suppression, i.e., the absence of bifoveal fusion-lock.

There are many intermediate types of reactions of conjugate shifts followed by slower fusional movements, but either of the above two clearly detected responses allows clear-cut screening for this aspect of binocular coordination.

How well are the two eyes used together? How secure the fusion-lock is may be determined objectively by (a) the cover-uncover tests or (b) the alternate-cover tests.

These well known, clinically used procedures are adequately detailed in texts and are merely illustrated here by Fig. 2 and 3.

The principal disadvantage of the objectively performed cover test for the purposes of a visual screening-testing technique is that it requires a trained professional for testing and interpretation. However, as will be seen, it is possible to extirpate the examiner from the testing procedure, and to machine-automate the maneuvers and interpretations.

The recommended test for the determination of the deviation in the primary position for present testing procedures embodies a combination of the subjective localization with a white Maddox rod dissociation, along with the cover-uncover test maneuver. The eye before which the Maddox rod is placed remains covered except for a brief flash exposure, sufficient for subjective, relative localization of the two dissimilar images, but insufficient time for fusional innervation eye movements to take place. The image separation is a measure of the basic deviation. This may be quantified with prisms.

It is important to randomize the zero point. The test should optimally be done with machine-controlled target and environment variables, and may easily be programmed for both distance and near habitual fixation circumstances. Dr. Sloan has shown that there is a good correlation between such machine-derived, test results and the usual free-space, clinically performed tests.

The improved head fixation in a machine-controlled device allows performance of the same test in different positions of gaze in order to detect oculorotatory defects.

One may predict that there is little or no change of the ocular deviation with age in adults except during incipient presbyopia. Here, enhanced efforts of residual accommodation may elicit excessive associated convergence. After the presbyopic correction is applied, it is not surprising that there may be a transient exophoria.

There is a slight but easily demonstrable restriction of upgaze with age that is augmented by debilitation, fatigue, and general systemic diseases.

Training, or enhancement of the security of fusion-lock by antisuppression, orthoptic procedures, or increase in the fusional amplitude, is possible. However, adults may not maintain these often transient benefits.

The future potential for a "best test" would have the following requirements:

1. cover-test advantages and criteria

2. machine-controlled variables (head fixation, target, and visual environment)

3. programmed, cover-uncover maneuver

4. recording of eye position and movements by corneal-reflection methods

5. automated interpretation.

The subject is required only to fix and read programmed isolated letters with each eye separately. The technician is required only to set zero on the recorded corneal reflection of each eye during its fixation. The technician also monitors the head position in the chin and forehead rest of the machine.

Fig. 6 shows a patient with a small-degree, right esotropia with suppression and amblyopia, and diagrammatic recordings.

The programmed introduction of the four-prism diopter prism before the right eye elicits no eye movements, nor does its removal. The four-prism diopter prism before the fixing left eye elicits a conjugate eye movement, and, similarly, a conjugate movement to re-fix by the left eye when the prism is removed.

Fig. 7 (exophoria) shows a diagrammatic recording of the covered right eye as the fusion innervation is slowly dissipated, and the fusion-free position is attained. The programmed uncover of the right eye shows a fast refusion movement. The programmed cover and uncover of the left eye shows similar movements of the left eye. Alternating the cover before each eye shows alternate fixation during the fusion-free deviation position.

Fig. 8 (esotropia right eye) shows a diagrammatic recording of the movement of the right eye after each eye is zero-set. This reveals a right esotropia under binocular conditions. This is confirmed as being real rather than an artifact, by the conjugate movement elicited when the left eye is covered and the right eye assumes central foveal fixation. Programmed uncover of the left eye shows a conjugate movement of both eyes in order for the habitually fixing left eye to regain fixation. Covering or uncovering the right eye, or a four-prism before the right eye, elicits no movement, while a programmed four-prism before the left eye elicits a conjugate movement as expected.

Thus, the four-prism diopter, binocular eye-movement test, and the nuances of the cover-uncover and alternate cover maneuvers may be machine-automated, and the resultant recording inspected, or automatically scanned and classified.

Some "in-between" fusion states, i.e., coexisting phoria-tropia

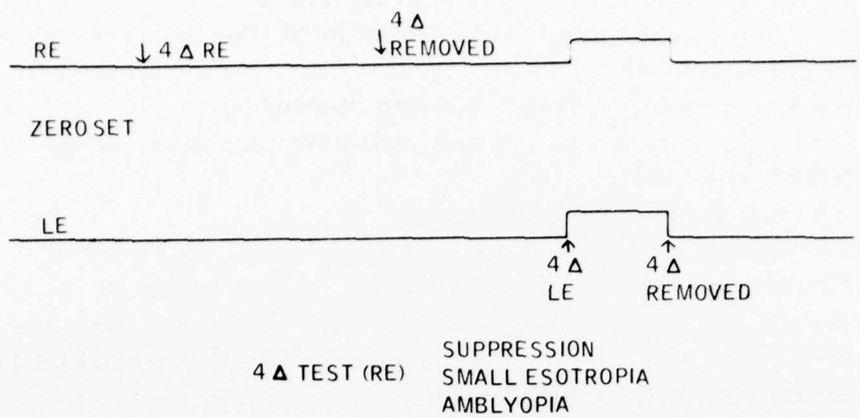


FIG. 6.*

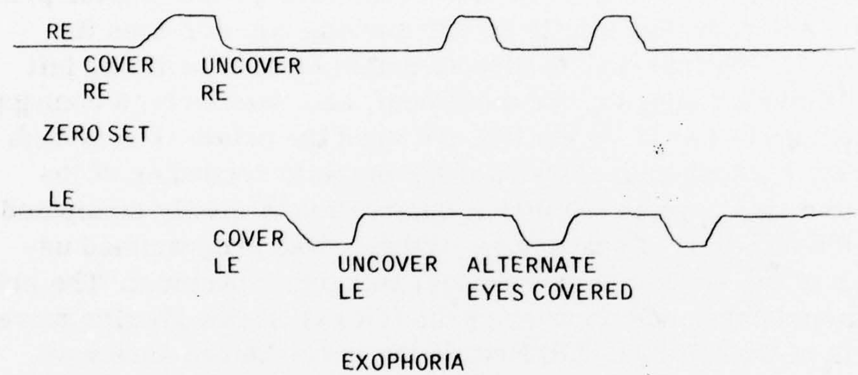


FIG. 7.*

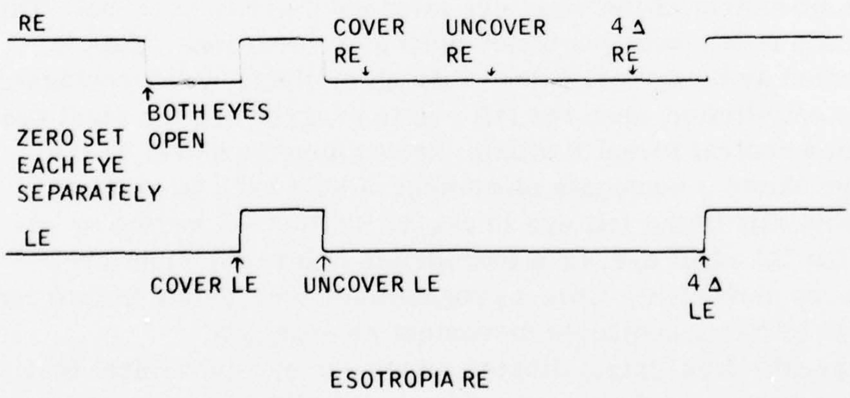


FIG. 8.*

*Diagrammatic representation of automatized recordings of characteristics of different types of ocular deviations. See text for explanation.

states, and sometimes combined conjugate-fusion vergence movements do not conform to the clearcut, diagrammatic examples shown.

Additionally, the motor stress determination of the recovery point of a fusional amplitude may be programmed so that the recovery point triggers the prism-diopter notation. Rotatory defects and eye-tracking tests may also be performed and recorded for the different non-primary positions of gaze.

Thus, a very adequate fully-automatized screening device to detect both the fusion status and the deviation in the primary or non-primary positions, may be employed to assess the binocular-coordination visual capability. Such a device is presently being constructed.

LABORATORY MEASUREMENTS OF THE OCULAR ROTATIONS, HETEROPHORIAS, AND OCULOMOTOR COORDINATION

Kenneth N. Ogle
Mayo Clinic and Mayo Graduate School of Medicine
University of Minnesota

The ability of a person to turn his two eyes in all directions of gaze in the visual field (the versions) is most important. Functionally, however, precision in regard to these ocular rotations is unnecessary. Limitations or defects in those rotations can be readily detected simply by observing them under clinical procedures. The determination of the oculomotor coordination of the eyes for the maintenance of binocular vision at all observation distances involves more subtle procedures.

For a pertinent study of oculomotor *imbalances*, some kind of a measurement is really needed when the eyes are being normally used binocularly with fusion. Only the fixation-disparity method provides such a measurement. However, when fusion is prevented, and one eye continues to fixate an object at a given distance, the other eye, under cover, turns to a position frequently called a fusion-free position, or a relative position of rest, that is to say, to a position relative to the stimulus to accommodation. It is assumed that the difference in the angle of this fusion-free convergence and that angle of convergence required for binocular fixation and fusion is a measure of the oculomotor imbalance, the rationale being that it represents, in a way, the amount of muscular energy constantly expended to maintain binocular fixation. Actually, of course, this energy expenditure varies between individuals and depends on several factors, among which are the prism vergences and the accommodative convergence/accommodation ratio.

Since only in sleep, and, perhaps, momentarily when the eyes are in extreme positions of lateral gaze, are the eyes ever normally disassociated—and, in sleep, there is no vision—is it any

wonder that Marlow thought habituation of stress within the oculomotor processes would forever prevent determination of the true heterophoria. Although prolonged occlusion of one eye did, in fact, show some changes in the heterophoria measurements, the interpretation of the changes found as to whether they represent the normal heterophoria may be questioned.

In any discussion of heterophorias, the question always arises to what extent they can give rise to ocular discomfort. Ophthalmologists are by no means in agreement on this question, some maintaining that a heterophoria never causes ocular discomfort except when it is near a prism-vergence limit—that is, when the imbalance is such that diplopia is prevented only with considerable effort. This point of view arises partly because of the large number of subjects known to have marked heterophorias, but who report no symptoms of ocular discomfort, and partly because in some patients, the wearing of ophthalmic prisms only slightly modifies the phoria. On the other hand, there are those ophthalmologists who believe there are great individual differences between persons in respect to ocular discomfort, and that for some persons the symptoms of discomfort can be alleviated by prisms even when the heterophorias are small. This situation is certainly true for some persons with vertical phorias, though this definitely does not apply to all or even to a majority of cases. It has been maintained in the Armed Forces that large heterophorias can cause discomfort to the point of their interfering with the man's job performance. Granting this point of view, the problem is to know what are the limits for and the situations under which a heterophoria is undesirable.

Consider, therefore, certain aspects of the determination of a heterophoria.

It is impossible, of course, to make a clear separation between the measurement of heterophoria in the laboratory and that made in clinical practice, or in screening tests. Most of the same problems are involved. In the latter case, however, where speed is essential, simpler tests must be made. Dr. Louise Sloan has summarized some of the various aspects of these measurements (Sloan, 1951), and, indeed, it is she who should be presenting this paper.

In either case, in setting up measuring devices most of the same problems must be recognized—problems of measurement and of interpretation. There is also the problem, not to be discussed here, of being able to distinguish between a heterophoria and a heterotropia.

There are moment-to-moment, physiological fluctuations in heterophorias which tend to set a limit to which the precision of measurement can be made. The magnitude of these fluctuations will vary from person to person, hour to hour, and may be exaggerated by small, uncorrected, refractive errors. Changes in heterophoria may occur also when the eyes are turned to different directions of gaze: the problem of anisophoria. False measurements of vertical phorias can occur when large exophorias are found.

The influence of the particular stimulus to accommodation inherent in any device for measurement of heterophoria, and the concomitant fluctuations that may occur in the accommodation itself, cannot be ignored.

Instrumental devices may themselves alter oculomotor imbalance, also, through psychological influences, for example, apparent nearness, or through physiological influences, such as field-limiting apertures.

Suppose this discussion is restricted here to concomitant heterophorias, that is, those heterophorias that stay reasonably constant over the principal portion of the visual field (±60 arc degrees). It must be admitted, however, that for a person in the Armed Forces a nonconcomitant heterophoria might be more serious than a large, concomitant heterophoria, for example, in situations depending on dynamic visual acuity.

The most practical test for concomitancy is the red-green test. Doctor Lancaster (Lancaster, 1939) also considered this test the most accurate for heterophorias. The subject wears goggles with red glass before one eye, and green glass before the other eye. He is seated before a large screen in a dimly illuminated room. The examiner then projects with a hand-held projector a narrow, bright-green line on the screen. The subject, in turn, directs a similar hand-held projector with a narrow, bright-red line to the screen, until this red line appears to him to superpose the green line. The actual separation of the two lines on the screen is the measure of the heterophoria, and its magnitude can be read by the examiner directly from scales (which are invisible to the subject) on the screen. The examiner can easily determine the heterophoria at any position on the screen. This test is made precise if certain precautions are maintained. Objections might be made in that the stimuli to accommodation are inadequate, and for distant vision a really large screen would be needed.

There is the prevailing tendency to believe that heterophorias

are best measured when the eyes are under natural conditions of observation, and when there is as little instrumentation as possible. Great reliance is placed on the simple, cover test because of this belief—even with the knowledge that the examiner cannot be sure how his subject is responding to the stimulus to accommodation. Although the cover-uncover test is considered the simplest and the most useful, it lacks precision when one attempts to measure the fusion-free deviation of the eyes.

Similarly, with the Maddox rod test, the belief is that the light stimulus should actually be at the distance measurements are to be made. It is true that Doctor Sloan has presented good evidence that the heterophorias measured for real distances are well correlated with those made in a simulated distance using a type of haploscope. However, for a near-observation distance this simulated distance may or may not be true because of the influence of proximal or distance convergence upon heterophorias, a phenomenon which varies greatly with subjects. A common stereoscope certainly is not recommended because of the difficulty of determining the stimulus to accommodation. Statistically, however, this proximal convergence is of the order of 1.5 prism diopters per diopter change in the stimulus to accommodation, i.e., change in distant vision to near vision.

Because of the synkinesis between accommodation and convergence, control of the stimulus to accommodation is most important in the precise measurement of lateral phorias. Generally, one can concur with Doctor Sloan that for measurements of phoria with the young subjects in the Armed Forces one should not correct the hyperopia, but rather measure the lateral phoria under the conditions in which the subject uses his eyes. On the other hand, if a large esophoria is found, and a large hyperopia suspected or measured, a refractive correction should be considered.

The problem of control of accommodation is important in any test, and the cover-uncover test, especially for near vision, is subject to error in this regard. With the Maddox rod, the streak image is not sharp and may have an adverse effect on the phoria measurement if the stimuli to accommodation for the fixing eye are not adequate. The use of a biprism before one eye, or a simple, vertical prism, has theoretical advantage in that both eyes are subject to the same stimulus to accommodation during the test.

Much can be said for the test for heterophoria with the Maddox rod in which the muscle light is imbedded in print, for the print

provides the adequate stimulus to accommodation. In this test, the eye observing the streak from the Maddox rod should, for the most part, be occluded, and then uncovered only momentarily, the exposure being just long enough for the subject to report whether the visual direction of the streak, when first seen, was the same as, or to the right, or to the left of the muscle light. It must be pointed out that, if the eye seeing the rod is not occluded, occasionally the subject can voluntarily, though perhaps unconsciously, control the pointing of the eyes to cause the streak image to move toward and even to superimpose the image of the light. Such an effect has been called a fusional movement, but this explanation probably is not correct. More to the point, however, is the fact that the blurredness of the streak gives a sense of nearness, especially when red, with a resulting innervation for accommodation, and a tendency of the test to show an error in heterophoria toward esophoria (Lancaster, 1939).

If one keeps in mind the precautions outlined above, and remains aware of the moment-to-moment fluctuations that tend to decrease precision, the Maddox rod tests can be made reasonably accurate.

It is proposed, also, that a most accurate test is the fixation-disparity test by which oculomotor imbalances can be measured while fusion is maintained and both eyes are subject to the same stimuli for accommodation. In this test, prismatic deviation corresponding to a zero disparity constitutes an associated, heterophoric measurement.

If prisms are used for near vision with tests such as the Maddox rod, it must be kept in mind that the angle of prismatic deviation will be less than that marked on the prism when used for distant vision. The decrease may be of the order of 10 to 15 per cent, depending on the distance of the prism from the eye. In the phorometer the error may be even greater. Care must be exercised, also, that the prism is properly oriented before the eye. Corrections for these errors are not usually made, either because the examiner is unaware of the error, or because it is to be understood that the near measurement will be stated in terms of the prism designation for distant vision.

Because of these various requirements, the need for speed, and the need for some standardization, it is clear why there would be a tendency to use some type of machine-testing. Especially would this be a useful procedure for screening purposes.

There is considerable evidence that phorias change very little with age, except insofar as the refractive correction may

have been changed. There is evidence, also, that phorias themselves are little changed with training. Phorias can be changed somewhat by certain drugs, peripherally by homatropine, for example, and systemically by barbiturates, alcohol, and, probably, by anoxia.

Some stress should be given to vertical phorias because, of all the heterophorias, these most often are the cause of ocular discomfort. Even relatively small degrees of vertical phorias may be disturbing to some persons.

Mention should be made also of the cyclophorias, which, although less often encountered, can give rise to discomfort. The degree of cyclophoria can be estimated in a phorometer when Maddox rods are placed before both eyes with axes at right angles to each other. With one eye occluded, the rod (vertical axis) is first adjusted so that the horizontal streak appears subjectively horizontal. The rod before the other eye is then adjusted so that the vertical streak appears subjectively vertical. With both eyes, then, the two should appear at right angles to each other. The actual difference between the axes of the rods measures the cyclophoria. Cyclophoria also can be detected (but not measured) in the Maddox wing test. It can be most accurately measured with a haploscope.

In conclusion, it is clear that, aside from the fixation-disparity method of measuring oculomotor imbalances, the means for measuring heterophorias accurately under laboratory conditions are essentially those that will be used under clinical conditions, except for greater care being taken in the design of the test and in the procedure of obtaining the measurements.

REFERENCES

Lancaster, W. B. Detecting, measuring, plotting and interpreting ocular deviations. Arch. Ophthal., 1939, 22, 867-880.

Sloan, Louise L. Comparison of ortho-rater and sight screener tests of heterophoria with standard clinical tests. Amer. J. Ophthal., 1951, 34, 1363-1375.

SUPPLEMENTAL REFERENCES

Cridland, N. The measurement of heterophoria. Brit. J. Ophthal., 1941, 25, 141-167; 189-229.

Ogle, K. N., & Dyer, J. A. Some observations on intermittent exotropia. Arch. Ophthal., 1965, 73, 58-73.

Scobee, R. G. The oculo-rotary muscles. St. Louis: Mosby & Co., 1947. Pp. 93ff.

ACCOMMODATIVE
AMPLITUDE
Gerald Westheimer, Chairman

PRECEDING PAGE NOT FILMED
BLANK

MEASUREMENT OF THE ACCOMMODATIVE AMPLITUDE

Gerald Westheimer
Neurosensory Laboratory, School of Optometry
University of California at Berkeley

In evaluating procedures for measuring the amplitude of accommodation, there are a few physiological and optical facts that should be kept in mind.

The process by which the refractive state of an eye is changed—accommodation—is now quite well understood. Contraction of the ciliary muscle allows slackening of the zonule of Zinn, and the lens assumes a shape that is dictated by the elastic forces operating on it, and the malleability of its substance. The progressive reduction in amplitude of accommodation with age is thought to be due to the inability of the capsule to shape the lens substance, which gets harder with age. A standard table of accommodative amplitude at given ages has been used for decades: recent work suggests that a small part of what has been regarded clinically as accommodation is really depth of focus of the eye.

Effective work has been done in measuring accommodation by recording changes in the curvature of the anterior surface of the lens, but cognizance needs to be taken of the fact that this can never be an absolute measurement. A certain amount, perhaps as much as one-half, of the added refractive power of the eye during accommodation is contributed not by changes in the outside surfaces of the lens, but by internal, refractive changes in the lens. This is called intracapsular accommodation.

The measurement of the amplitude of accommodation in a subject must be undertaken with the realization that one is dealing with a cybernetic system, not with an open-loop, physiological system. If a subject is focused for infinity and a close-up target is presented to him a focus error is introduced (Fig. 1). For an accommodation response to ensue, this focus error has

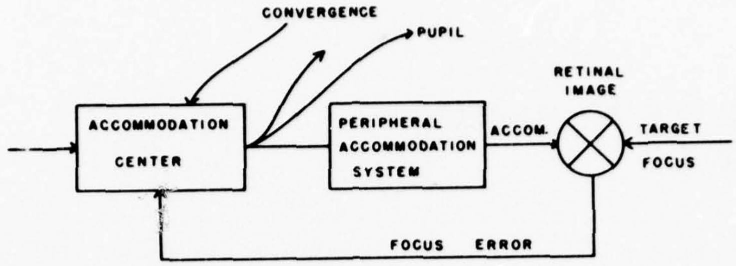


FIG. 1. Block diagram illustrating processes involved in accommodation responses.

to be detected at the sensory level, and then a feedback system has to be brought into operation to eliminate it. Attempts to look at the accommodation system from this point of view are meeting with limited success. Certain features commonly associated with servo-systems, such as steady-state errors and oscillations in the output, are, indeed, found in accommodation.

The situation is, however, beset by many complications. It appears that the focus-error detecting system in its purest form is not direction-sensitive. Ordinarily, the direction of response is not in error, because of decisions by higher, perceptual processes. That more is involved than just a simple servo-system is also indicated by the fact that the steady-state error is a function of the information content of the stimulus—it is much higher in such conditions as dim illumination, and lack of detail in the stimuli.

The importance of these findings in the clinical measurement of accommodation is that they emphasize the necessity to manipulate the stimulation conditions optimally for a full response to be obtained.

SUPPLEMENTARY REFERENCES

Alpern, N. Accommodation. In H. Davson, (Ed.), The eye. New York: Academic Press, 1962. (Vol. 3)

Westheimer, G. Optical and motor factors in the formation of the retinal image. J. opt. Soc. Amer., 1963, 53, 86-93.

Westheimer, G. Focusing responses of the human eye. Washington: Armed Forces-NRC Comm. on Vision, Proc., 1963 Meeting.

LABORATORY MEASUREMENT OF ACCOMMODATION

F. W. Campbell
The Physiological Laboratory
Cambridge, England

In 1937, Geoffrey Collins patented (U.S. Patent No. 2,164,576) and manufactured in London a prototype model of the first "Electronic Refractionometer." It used infrared light to prevent pupil contraction and photoelectric detection of the signal. It was primarily designed to estimate the magnitude of refractive errors, but changes in accommodative power were also observed with it (Collins, 1937). Some 20 years were to pass before this elegant instrument was resurrected in a modern form.

The next photoelectric recording optometer was described by Glezer and Zagorulko (1955). Instead of detecting changes in the focus of an image formed on the retina, they recorded the displacement of the third Purkinje-Sanson image formed at the anterior surface of the eye's lens. Its sensitivity was low, about 0.5 diopters (D), and it was susceptible to eye- and head-movement artifacts.

Campbell and Robson (1959) developed a high-speed, infrared optometer sensitive enough to investigate the microfluctuations of accommodation previously described by Arnulf, Dupuy, and Flamant (1955). The design was further simplified optically, and altered to permit the use of modern, solid-state phototransistors that have a high quantum efficiency in the near infrared (Campbell, Robson, & Westheimer, 1959). This research optometer was linear over a range of about 2 D, but was unsuitable for clinical measurements requiring a greater range and less sensitivity. It did, however, serve to establish objectively the dynamics of the so-called "accommodation reflex" (Campbell & Westheimer, 1960).

The recording optometer of Allen and Carter (1960) again

used infrared light, but detection was by means of a large-area photocathode, a photomultiplier. Although the quantum efficiency of this type of photocell is low compared with solid-state detectors, its linear properties were used to advantage by designing the optometer to have a linear signal over a much wider range of accommodation change. A later prototype of this instrument is now available, and is suitable for some types of clinical research.

The instrument of Roth (1962) was designed for the study of accommodation changes in laboratory animals. Due to the rather elaborate chopping-system, much light energy is lost. It is probably of rather low sensitivity if used for humans or animals with a dark fundus.

The optometer of Elul, Marchiafava, and Nicotra (1964) has many interesting design points in its optics. It appears to have very good sensitivity and linearity when used with the cat. It is, however, subject to artifacts if there is any fore and aft movement of the eyeball in the socket. It has certainly been useful in the study of accommodation in that animal.

Warshawsky (1964) was the first to attempt the linearization of an optometer by incorporating a feedback movement to the position of the effective light-source and photodetectors. This permitted the use of small, efficient, solid-state photodetectors, although they are, themselves, nonlinear. One interesting and important experiment can be done with this instrument—the effect of opening the accommodative feedback loop.

Larks (1964) describes a "microminiature, automatic recording, infrated coincidence optometer detector module," which deserves careful consideration, as it is the first one to detect focus using only the beam coming out of the pupil of the eye. The entire module weighs only five ounces, and on this consideration would be suitable for research during space flight. Additional lighting and electronic equipment would also be required. Unfortunately, the author gives no indication of its sensitivity or linearity.

It is interesting to note that each group of workers investigating accommodation has designed its own recording optometer. The reason is clear—each group has a rather different type of data to collect, and no universal optometer is likely to be useful in all instances. Sensitivity, linearity, speed of response, convenience, freedom from eye-movement artifacts, weight, and cost have all to be considered. The important fact remains that

sufficient light returns after reflection from the fundus to permit infrared photodetectors to operate.

Can any improvements be expected in the future? Solid-state photodetectors already have such a high quantum efficiency as compared with an ideal detector that it is unlikely that improvements will be significant. The other limiting factor is the intrinsic luminance of the light source (not the total power of the source, but its luminance per unit-area). Clearly, the latter is the ideal source for this purpose, especially as it can operate in the infrared region. The only upper limit here is the amount of light brought to a focus on the lens or retina, for, ultimately, heat damage to these tissues must result. A considerable improvement in signal-to-noise ratio should be achieved before this pathological limit is reached.

While there are already many practicable, recording optometers suitable for laboratory use, it cannot be said that a fully automatic one is available which the patient can use for himself to dispense his personal optometric prescription! Westheimer (1957) gives an entertaining, Wellsian glimpse into this clinical future.

REFERENCES[1]

Allen, M. J., & Carter, J. H. An infrared optometer to study the accommodative mechanism. Amer. J. Optom., 1960, 37, 403.

Arnulf, A., Dupuy, O., & Flamant, Francoial. Les microfluctuations d'accommodation de l'oeil. Ann. opt. ocul., 1955, 3, 109.

Campbell, F. W., & Robson, J. G. High-speed infrared optometer. J. opt. Soc. Amer., 1959, 49, 268.

Campbell, F. W., & Westheimer, G. Dynamics of accommodation responses of the human eye. J. Physiol., 1960, 151, 285.

Campbell, F. W., Robson, J. G., & Westheimer, G. Fluctuations of accommodation under steady viewing conditions. J. Physiol., 1959, 145, 579.

Collins, G. The electronic refractionometer. Brit. J. physiol. Opt., 1939, 1, 30.

Elul, R., Marchiafava, P. L., & Nicotra, L. Method for measurement of accommodation in the cat. J. opt. Soc. Amer., 1964, 54, 380.

Glezer, V. D., & Zagorulko, L. T. Fiz. Zhur. S.S.S.R., 1955, 41, 830

Larks, L. A microminiature, automatic recording, infrared coincidence optometer detector, module. L. sci. Instrum., 1964, 41, 780.

1. This list is not intended to be comprehensive. Individual authors should be contacted to obtain all publications and reports.

Roth, N. Recording infrared coincidence optometer. Amer. J. Optom., 1962, 39, 356.

Warshawsky, J. High-resolution optometer for the continuous measurement of accommodation. J. opt. Soc. Amer., 1964, 54, 375.

Westheimer, G. Refraction by automation. Amer. J. Optom., 1957, 34, 339.

NIGHT VISION

Jo An Kinney, Chairman

CLINICAL MEASUREMENT OF NIGHT VISION

Jo Ann S. Kinney
Submarine Medical Research Laboratory,
U.S. Naval Submarine Medical Center

In 1961, the work that had been done in the 50's on night vision-testing was reviewed by the author for the Committee on Vision. It was pointed out, at that time, that the picture was much brighter than it had been in the late 40's (Berry, 1949), that the testing of night visual ability rested on a much firmer foundation of basic research, and that there was every reason to believe that individual differences in night vision were sizeable, meaningful, and could be valid predictors of performance at night (Kinney, 1962).

When this task of reporting on the clinical testing of night vision was undertaken, immediate inquiries were made in a number of places about the types of mass testing currently going on. A large and growing body of literature coming from the group interested in night driving was found. This includes some clinical testing, studies of tracking, depth perception, dynamic visual acuity, investigations of the effects of age, and a variety of other interesting and pertinent topics (Allen & Lyle, 1963; Richards, 1964; 1965; Schmidt, 1961).[1,2]

The night driving group performs most of its investigations at the specific illumination levels employed in night driving. Since headlights are always used, these levels are mesopic or low photopic, rarely falling below .01 ft-L and are above the range of the major interest here. Nonetheless, the topics being investigated are of general interest for low-level visual perform-

1. O. W. Richard, Personal communication, 1965.

2. R. W. Reading & H. W. Hofstetter. Extrahoroptinal stereopsis in vehicle-operator orientation. Personal communication, 1965.

ance, and extending the work to even lower levels should be very informative.

However, no organized program of night vision testing was found. As far as the Armed Forces are concerned, there are only isolated groups doing work on specific, practical problems. Of the two new tests reported in 1961 by the author, both of which were based upon considerable research, the Army Night Seeing Tester was on loan to France and NASA, while the NMRL Night Sensitivity Test was on loan to the U.S. Army.

It, was therefore, the decision of the author to do some mass testing, utilizing some of the techniques and information gained in the past 20 years, in an attempt to answer some specific, practical questions concerning the measurement of low-level vision.

Major problems involved in assessing low-level vision are the lack of correlation between photopic and scotopic vision and the fact that both types of vision may be involved to a greater or lesser extent at certain, intermediate light levels. It was decided to use a battery of tests, each selected to assess a particular aspect of vision. One hundred Naval enlisted men were given the battery.

There are, of course, sizeable individual differences in photopic or cone vision and numerous methods of measuring them. Since the major interest was in vision at the lower light levels, photopic acuity screening was included only to ascertain that subjects who had adequate daylight vision were being tested.

Part of the regular physical examination for submarine school candidates is a test of uncorrected vision using a Snellen letter chart. If a man fails to read the 20/20 line, he is referred to the naval optometrist for further examination. The data obtained include his refractive error and his corrected visual acuity. The 100 men included 50 men who passed the original screening and 50 rechecks, or those who did not pass. The latter group consisted almost entirely of myopes who needed glasses to obtain 20/20 vision, and they continued to use their glasses for the low-level tests. The photopic data consisted of a score of 20/20 or 20/15 for each man, and the notation of whether or not he used glasses.

There were also sizeable individual differences in scotopic sensitivity, or rod vision, and good correlations were obtained between scotopic sensitivity and acuity and brightness discrimination, as long as precautions were taken to stay within the scotopic range, and to measure at the same retinal position. The

NMRL night vision sensitivity test was chosen to measure this ability since it had been successful in the past.

The test provides a measure of scotopic vision based upon sampling the subject's sensitivity at a number of retinal positions between 5° and 20° from fixation. Briefly, it consists of small stimuli of various sizes presented at various positions, which the subject identifies as being above, below, to the right, or to the left of a central fixation point. A total of 120 stimuli are presented, and typical distributions of the total number correct vary from about 30 to 100; the test-retest correlation is .85 to .90 (Kinney, Sweeney, & Ryan, 1960a)

At the intermediate, mesopic level, there are numerous possibilities for interaction, and acuity tests at two luminance levels were included to assess these. Measurement was made with black Landolt rings of variable size at two light levels, .005 ft-L or 6.7 log micro-micro-Lambert ($\mu\mu$L), and .0009 ft-L or 6.0 log $\mu\mu$L. Testing was done binocularly at 14 ft and the subject's entire visual field was evenly illuminated. The use of offcenter vision was explained to each subject. He was told to look first at the targets directly, but, if he could not see the gap this way, to try off-center vision. Five Landolt rings of different sizes were presented at once, and the subject read across giving the position of the gaps; the target positions were then changed mechanically, and the procedure was repeated until eight judgments were made for each of the five ring sizes, or a total of 40 judgments. The mesopic data are the liminal values, in minutes of arc, of the targets that could be resolved.

This type of test is similar to those used in the Army Night Seeing Tester, which the author would like to have included in the battery, since it measures acuity at the same level as the highest by this test, 6.7 log $\mu\mu$L. While the Army test uses two types of targets, a line resolution, and a brightness discrimination task (Uhlaner & Zeidner, 1961), two light levels were used here. The outcome is probably the same—that is, different degrees of rod-cone interaction or different retinal areas are required for success on the two different tasks, or at the two different light levels.

The testing procedure for the 100 men was as follows. After the photopic screening, the subject adapted for 5 min to the higher mesopic level. The first mesopic test was given, which consumed an additional 5 min; the illumination level was then reduced, and the adaptation and testing procedure repeated. The subject was then dark-adapted for 10 min and the night vision

test was given. The whole testing procedure totalled 45 min/man.

Before presenting the data, two points should be mentioned. First, the men were all young, averaging 21 years of age, and there is no correlation between age and any of the visual functions measured for this group. There is, of course, a negative correlation between age and night vision if a sufficiently wide sample of ages is included. Generally speaking, however, this loss does not manifest itself until about 30 years of age, nor become sizeable until 50, and it is thus not likely to be a selection problem for the Armed Forces (Crawford, 1949; Luria, 1960; Ruddock, 1965).[3]

Second, the data for those men who passed the original acuity screening were at first analyzed separately from those of the rechecks. However, the results showed very small differences between the two groups on each test, the size of the difference being what one would predict from the light loss due to the absorption by spectacles. Therefore, all subjects have been treated together for this presentation since the interest was in the practical aspect of the men's visual ability. If they needed glasses they used them, and their vision through the glasses is the important datum.

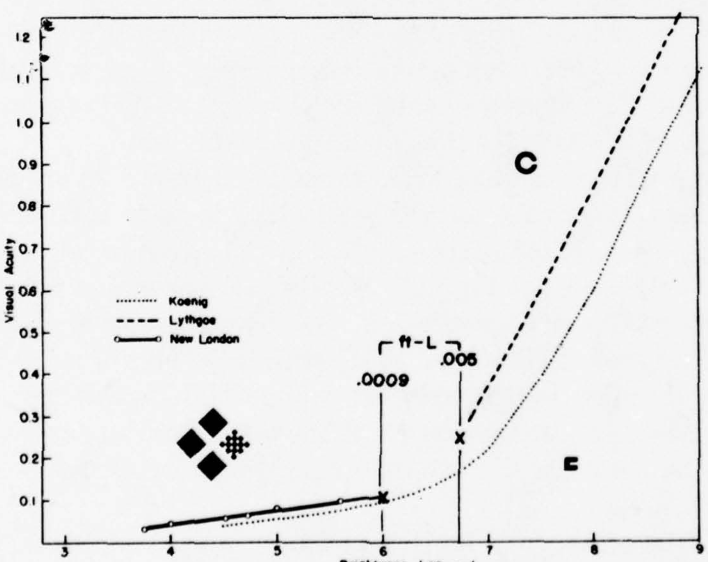


FIG. 1.

3. O. W. Richards. Personal communication, 1965.

Figure 1 shows the luminance levels used in the mesopic testing on the typical graph of acuity versus illumination (Morris & Dimmick, 1950). The levels were chosen to lie on either side of the photopic and scotopic functions; thus, the higher mesopic level would presumably be more related to cone functioning, and the lower mesopic level to rod functioning. The average data for the group fell almost exactly on the appropriate lines and thus could be predicted from the published linear scotopic or photopic acuity functions.

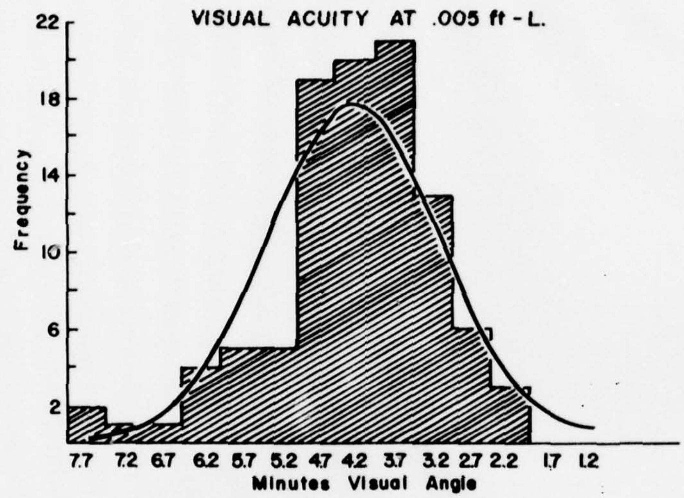


FIG. 2.

Fig. 2 shows the frequency distribution of the 100 men at .005 ft-L in terms of the liminal value in minutes visual angle. The values increase from right to left, so that best vision is always to the right in this and the following figures. Despite the fact that the men all had good photopic acuity, 20/20 or better, the mesopic data form the fairly normal distribution—with some skewness on the low side—that is typical of visual functions. The data cover a sizeable range, a variation of 2 to 8 min of visual angle (or in Snellen fractions, from 20/40 to 20/160).

Fig. 3 shows the frequency distribution for the acuities at the lower mesopic level. The distribution is similar, but it has a hint of bimodality as would be expected from a second independent variable, and the individual variation is also extreme—from 5.5 min to 21 min.

The distribution of scores on the night vision test is shown in Fig. 4 and is very typical of previous results with the test. The range extends from 40 to 95 out of a possible 120.

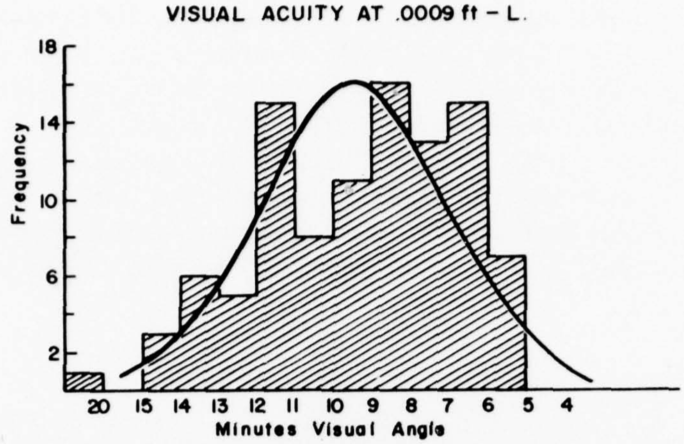


FIG. 3.

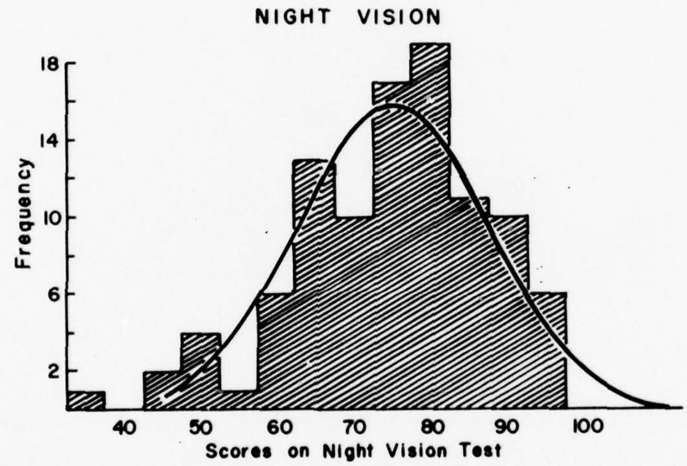


FIG. 4.

Fig. 5 summarizes the correlation coefficients determined for the various tests. The only sizeable correlation, .75, is between the two mesopic tests. Significant, small correlations are also found between the photopic and mesopic tests and between the low mesopic and scotopic test. This sample of data, thus, is in complete agreement with previous work of numerous investigators; the almost universal finding has been that there is essentially no correlation between photopic and scotopic vision, and that the correlation increases in size as the light levels used in testing are brought closer together (Ogilvie, Ryan, Cowan, & Querengesser, 1955; Pirenne, Marriott, & O'Doherty, 1957; Uhlaner, Gordon, Woods, & Zeidner, 1953).

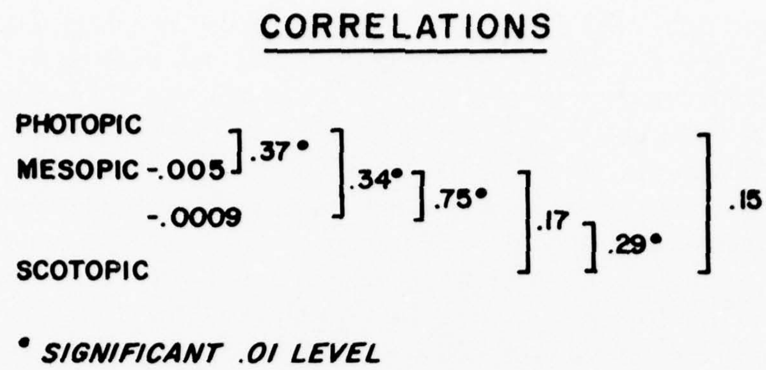


FIG. 5.

In order to try to answer, with the aid of these data, some very practical questions concerning the selection of men, the 20 best men and the 20 poorest men on each test were selected to compare and contrast.

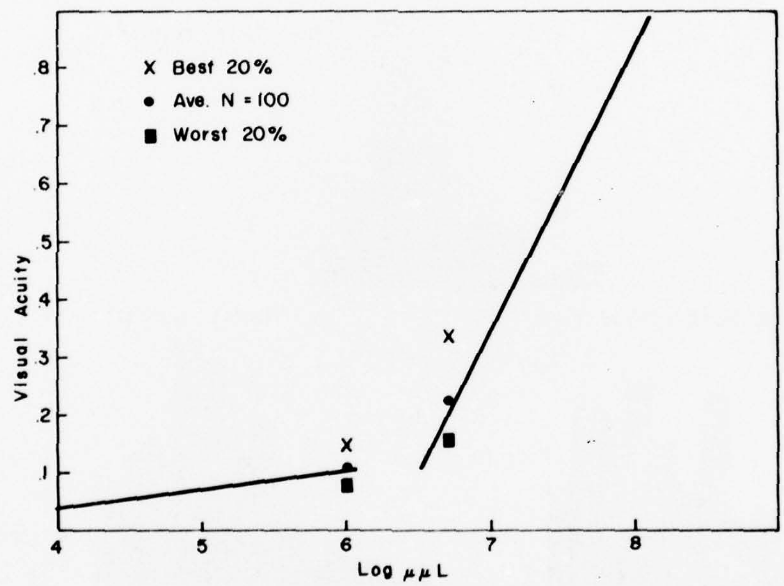


FIG. 6.

The first question concerns the meaning of the size of individual differences found on the various tests. Fig. 6 shows a portion of the acuity-illumination functions with the data for the best and the worst 20 per cent of the men for the low and the high mesopic acuity tests. It is obvious that the best men at the low light level have the same acuity as the worst men at the higher light level—7/10 of a log unit above. At the high mesopic level, the normal or average man would need 7 log $\mu\mu$L to see

what the best man sees at 6.7, or, in other words, twice as much light. At the low mesopic level, the differences are even more extreme—the average man could see at 5 log $\mu\mu L$ what the poorest man sees at 6 log $\mu\mu L$—a ten-fold difference in illumination. The range and levels are such that one could predict that the best man could see with starlight the same detail as the poorest man with light from a half-moon.

Similar examples of the meaning of individual differences in night vision sensitivity have been calculated previously—to cite just one: a 100-candle power beacon could be seen by the least sensitive man at approximately 12 miles, and by the most sensitive man at 18 miles (Kinney, Sweeney, & Ryan, 1960b). This example does take into account the greater attenuation of the distant light by the atmosphere for the most sensitive man. Thus, one is dealing with sizeable and very important differences in visual ability.

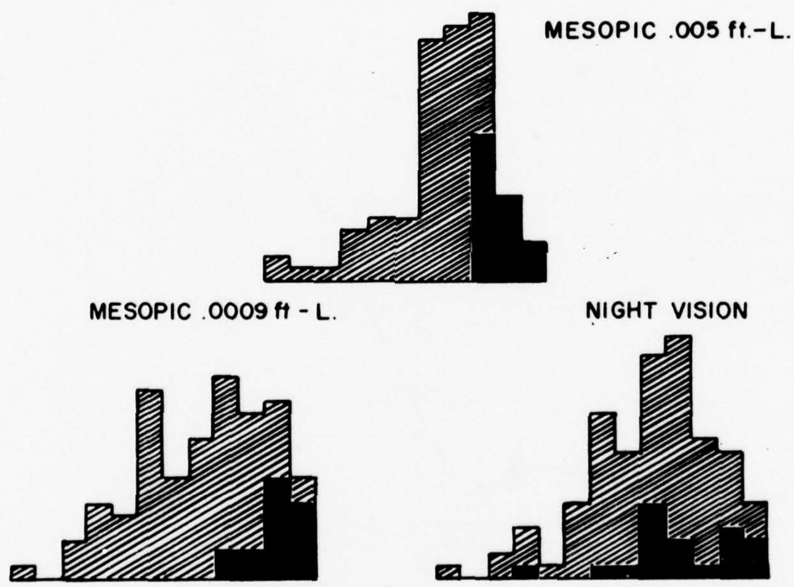


FIG. 7.

The second question concerns the use of mesopic testing, which requires little adaptation time, if one wishes to select men for ability at lower levels. In this regard the results of how the best and poorest men on the mesopic tests perform on tests at lower levels are shown. Fig. 7 uses the high mesopic test as the selection device. The solid areas show where the best 20 per cent, as thus selected, appear in the distributions at the low mesopic level and on the night vision test. At the low me-

sopic level, the results are quite good, although there has been some shift in position. Sixty-five per cent of the selected men are still in the top 20 per cent of the low mesopic test. On the night vision test, while the average score of these selected men is above the overall average for the 100 men, a few of the men do quite poorly.

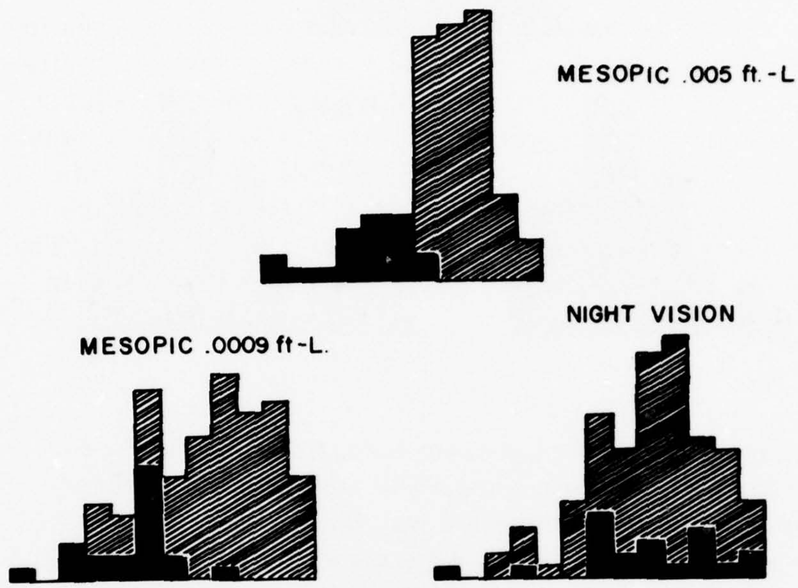


FIG. 8.

A similar analysis is shown in Fig. 8 for the poorest 20 per cent of the men, as selected by the high mesopic test. Some shift in position has occurred on the low mesopic test—60 per cent of the men, selected as poorest on both tests, are the same. On the other hand, the scores of these men on the night vision test cover the entire range of values found in the total population.

The picture is slightly improved for selection by the low-level mesopic test, as indicated in Fig. 9, but the range of scores on the night vision test is still very large. It is obvious that many men with excellent scotopic sensitivity would be excluded on the basis of this mesopic test, while some men would be selected whose low-level sensitivity is rather poor. Thirty-five per cent of the men who appear in the best group at the low-level mesopic test also appear in the best group on the night vision test.

An interesting parallel can be drawn between these results, all of which were obtained in a laboratory-testing situation, and the field validation studies done on the Army Night Seeing Tester (Uhlaner & Zeidner, 1961). In the latter investigations, selection

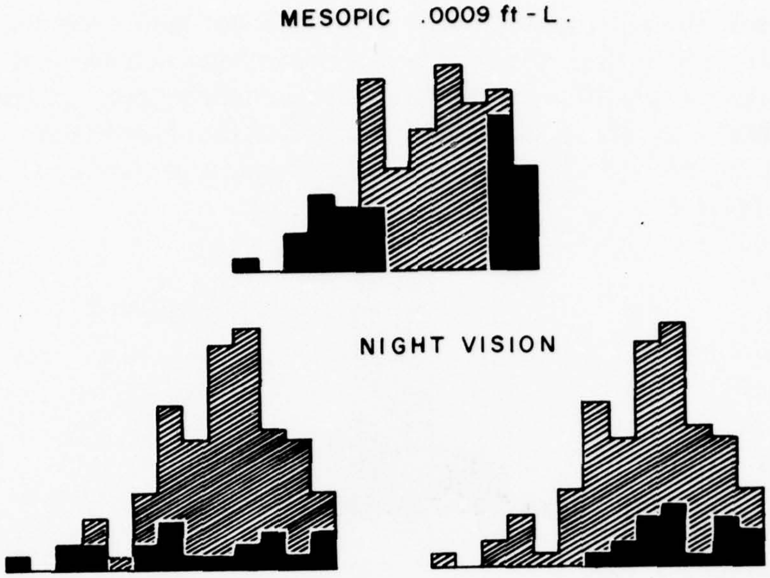


FIG. 9.

of two groups, the best and poorest men, was made using the Tester at the high mesopic level. The performance of these groups in a starlit, field situation was then compared. The results are quite similar to these in general form. First, the average performance of the best group was significantly superior to that of the worst group. Second, the distribution of scores was similar in that none of the best men were among the very poorest at the lower light level, but some of the poorest men do achieve excellent low-level results.

Two other combinations of test results are at least theoretically possible. The men could be selected only if they appeared in the top 20 per cent on both the high mesopic test and the night vision test. While such a procedure is hardly a time-saving one, since full dark adaptation is required, it is encouraging to find that 87 per cent of the men thus selected also fall in the best 20 per cent at the low mesopic level. The total number of men selected, however, has fallen to a very low level—seven.

The last possibility, that of using all three tests for selection, results in only six men out of the total 100 who appear in the top 20 per cent on all three tests. Similarly, three men appear in the worst 20 per cent on all three tests. These figures are very close to the number calculated from the straight probabilities of being included in the top or bottom 20 per cent of two independent samples.

This leads to the last question which concerns the extent to which the data follow the hypothesis of two discrete functions, scotopic and photopic, both of which may show normal, unrelated, individual variation. This becomes important, not only for theoretical reasons, but also for predicting ability at low illumination levels from the trend at higher levels. For example, all subjects required a larger target at the lower mesopic level than at the higher—the average for the total group was an increase in size by a factor of 2.2. Since the low mesopic level presumably necessitates considerably more rod-functioning, one could predict that those individuals whose relative acuity loss from high to low mesopic levels is much larger than average, have exceptionally poor night vision and, conversely, those whose loss is less than average, have superior night vision. Such an analysis was performed for this set of data and yielded the result that the men whose low-level mesopic acuity was considerably poorer than predicted, did, indeed, have poor night vision. There were 15 such individuals and their average night vision score was just about one full standard deviation below that of the total group.

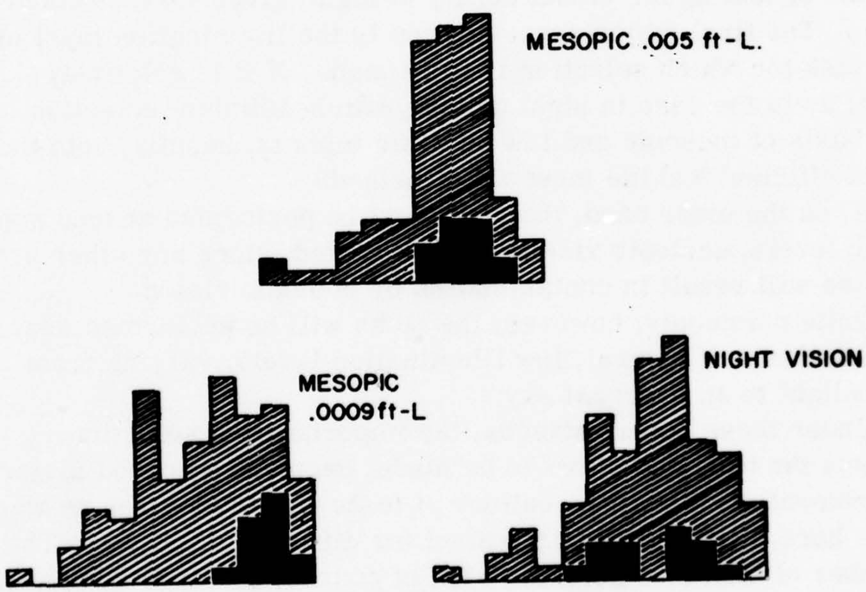


FIG. 10.

However, a similar analysis of the men whose low-level mesopic acuity was much better than predicted yielded negative results in that they had quite average night vision test scores.

Also included is Fig. 10 showing the frequency distribution of the data for this group, since it was very homogeneous, as

well as intriguing. Their scores were very close to average on photopic acuity, the high mesopic test, and the night vision test, but at the low mesopic level, they are all obviously superior to the rest of the group. Numerous possible reasons would account for this—differences, for example, in the degree or onset of night myopia, in the retinal position used, or in rod-cone summative mechanisms. Whatever the explanation, they do show an excellence in integrated rod-cone vision not predicted by their scores for photopic or scotopic vision alone.

Thus, the major portion of the data are in accord with the hypothesis of two independent functions: this includes the lack of correlation between photopic and scotopic vision, the partial success of mesopic selection for scotopic vision, the total number of men selected as outstanding on all tests, and the poor night vision evidenced by those men for whom it was predicted. On the other hand, such a simple hypothesis will not account for everything, and allowance should be made for individual differences in the interaction between scotopic and photopic vision.

By way of summary is stated what appears to be the best means of testing for visual ability at night, given various conditions. The first major consideration is the illumination level of the task for which selection is to be made. If it is relatively high, as is the case in night driving with headlights, selection on the basis of mesopic and low photopic tests is, happily, both the most efficient and the most valid method.

If, on the other hand, the task must be performed at true scotopic levels, scotopic vision must be tested, since any other procedure will result in contamination by photopic vision.

Quite commonly, however, the tasks will be performed over a wide range of natural, low illumination levels, varying from moonlight to an overcast sky.

Under these circumstances, the importance of selection, versus the time and effort to be made, becomes a second major consideration. Ideally, a battery of tests should be given as was done here, each designed to select for different attributes. The number of men thus selected will, of course, be small compared to the effort spent in testing, and such an effort probably will be expended only if the need for excellent, low-level vision is very great.

As a possible short-cut, testing and selection at two mesopic levels is suggested, with elimination of those men whose lower level acuity is poorer than expected on the basis of their higher

level acuity. While this cannot guarantee the best men for true scotopic work, it will do much to eliminate the poorest.

One final point: one could argue that night vision should not be a separate category at all on this agenda, since it could include nearly all the other nine functions presented in these papers, simply measured at a low light level. Certainly it includes visual acuity; refractive error at low levels is an obvious variable, as in night myopia; depth perception, phorias, and visual fields, all could be extended into the low luminance ranges.

The more restricted view has been taken that there is a single function—basic, static, dark-adapted rod vision—which can be measured and gives rise to large, individual differences, both by itself, and in combination with dark-adapted cone vision. The battery was chosen by the author to measure this type of sensitivity, and ten categories of visual competence could be easily obtained by a division of the normal distribution. Numerous other more dynamic tests could be included such as recovery time or resistance to glare.

REFERENCES

Allen, M. J., & Lyle, W. M. The relationship between night driving ability and the amount of light needed for a specific performance on a low contrast target. J. Amer. Optom. Assoc., 1963, 34, 1301-1303.

Berry, W. Review of wartime studies of dark adaptation, night vision tests, and related topics. Washington: Armed Forces-NRC Vision Comm., 1949.

Crawford, B. H. The scotopic visibility function. Proc. Phys. Soc., 1949, 62B, 321-334.

Kinney, J. Ann S. Review of recent literature on night vision testing. In M. A. Whitcomb (Ed.), Visual problems of the Armed Forces. Washington: Nat. Acad. Sci. - Nat. Res. Council, 1962. Pp. 3-11.

Kinney, Jo Ann S., Sweeney, E. J., & Ryan, Alma P. A new test of scotopic sensitivity. Amer. J. Psychol., 1960, 73, 461-467. (a)

Kinney, Jo Ann S., Sweeney, E. J., & Ryan, Alma P. A new night vision sensitivity test. U.S. Armed Forces Med. J., 1960, 11, 1020-1029. (b)

Luria, S. M. Absolute visual threshold and age. J. opt. Soc. Amer., 1960, 50, 86-87.

Morris, Ailene, & Dimmick, F. L. Visual acuity at scotopic levels of illumination. USN Submarine Base, New London, Conn.: Med. Res. Lab. Rep., 1950, No. 162, 9, 157-183.

Ogilvie, J. C., Ryan, J. E. B., Cowan, R. F., & Querengesser, E. I. Interrelations and reproducibility of absolute light threshold and scotopic acuity. J. appl. Physiol., 1955, 7, 519-522.

Pirenne, M. H., Marriott, F. H. C., & O'Doherty, E. F. Individual differences in night-vision efficiency. *H. M. Stationery Off., London:* Med. Res. Counc. Spec. Rep. Ser., 1957, No. 294.

Richards, O. W. Vision at levels of night road illumination, IX Literature 1963; X Literature 1964. Washington: NRC Highway Research Board reports to Night Visibility Comm. 1964; 1965.

Ruddock, K. H. The effect of age upon color vision-II. Changes with age in light transmission of the ocular media. Vis. Res., 1965, 5, 47-58.

Schmidt, Ingeborg. Are meaningful night vision tests for drivers feasible? Amer. J. Optom. & Arch. Amer. Acad. Optom., 1961, 38, 295-348.

Uhlaner, J. E., & Zeidner, J. The Army Night Seeing Tester—development and use. Washington: TAGO, DA., HFRB tech. res. Rep., 1961, No. 1120.

Uhlaner, J. E., Gordon, D. A., Woods, I. A., & Zeidner, J. The relation between scotopic visual acuity and acuity at photopic and mesopic brightness levels. J. appl. Psychol., 1953, 37, 223-229.

NIGHT VISION AND VISUAL SENSITIVITY[1]

Howard D. Baker
Florida State University

A fundamental characteristic of night vision is that it is vision under conditions of increased visual sensitivity. Night-vision testing, thus, often is considered to be the attempted measurement of visual sensitivity. The aim of the present paper is to look at the term "visual sensitivity," and, perhaps, to assess its meaning.

Measures of Sensitivity

Sensitivity is measured in several ways: by the absolute threshold, by the difference threshold, and by visual acuity. Does it mean the same thing in each case? Consider the parallel example of luminosity. Luminosity seems to be a relatively fixed characteristic of the organism, whether it is measured by the absolute threshold, by the difference threshold, by flicker photometry, or by heterochromatic match. The results are always about the same, and the interesting questions about luminosity have become questions about the exact shape of the curve and its implications. Is sensitivity like luminosity? Is it some characteristic that one can apply to the subject, and use to understand the way he acts in a variety of visual situations?

Perhaps an answer to the question lies in the following proposition. When the same things are done to the organism to change its sensitivity, but sensitivity is measured in different ways, the sensitivity changes should be consistent in each case. Thus one may try to use the dark adaptation curve measured with the

1. The preparation of this article and the unreferenced research was supported by contract with the Office of Naval Research.

absolute threshold to predict the difference-threshold dark adaptation curve. Or, one may try to predict the visual acuity dark adaptation curve from either. If the dark adaptation curves are found to be consistent with one another, one may then repeat the comparisons with light adaptation curves.

Dark adaptation and light adaptation are surely two of the most significant functions for night vision. They purport to be changes in sensitivity, they have had a great deal of research attention, and they will serve as evidence in this paper.

Sensitivity during Dark Adaptation

The classical dark adaptation picture is shown in Fig. 1. Note the rod-cone break, the absence of a break in dim, pre-adapting lights and the smooth family of curves.

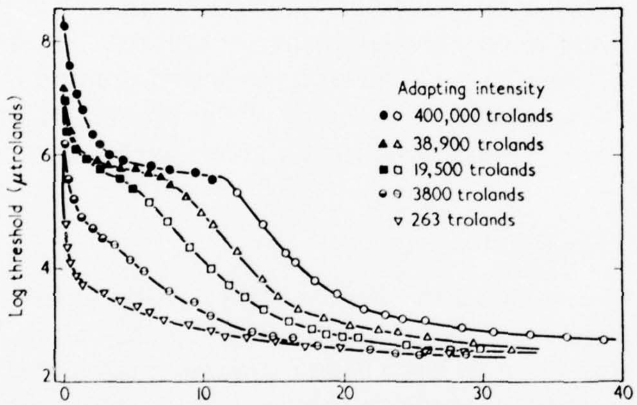


FIG. 1. Dark adaptation measured with absolute threshold, following several levels of pre-adapting light as indicated. (Hecht, Haig, & Chase, 1937)

Figure 1 is based on absolute threshold data. How should one expect dark adaptation curves to look if the difference threshold, instead of the absolute threshold, is used to measure the sensitivity change? First one needs to know the relationship between the absolute threshold and the difference threshold under terminal or equilibrium conditions. Figure 2 defines the relationship between the absolute threshold and the difference threshold at various adapting levels. From Fig. 2 it would be expected that the dark adaptation curve should show smooth changes in sensitivity from one level to another, with rod-cone breaks occurring whenever the threshold passes from a level above about 0 log trolands to a level below, and with no breaks otherwise. Fig. 3 shows that it, indeed, does so; the curves of Figs. 1 and 3 seem quite compatible.

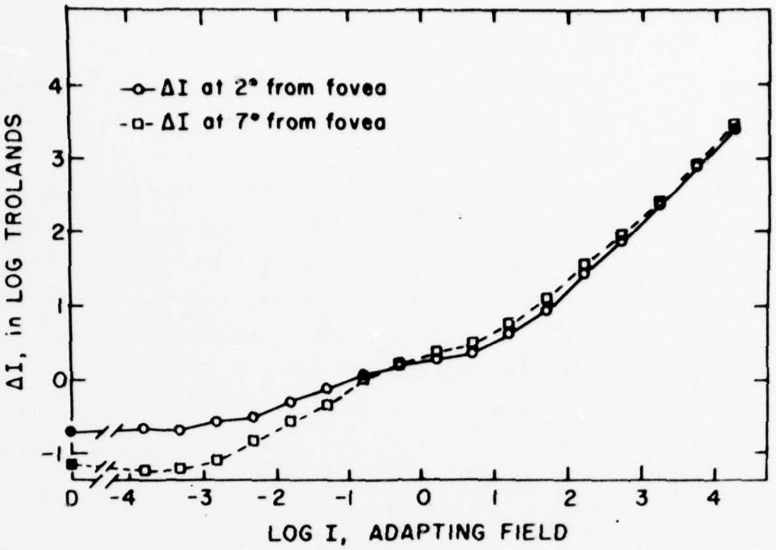


FIG. 2. Equilibrium relationship between absolute threshold (black points) and difference threshold to various background luminances (unfilled points) in one subject. (Florida State Univer. Laboratory)

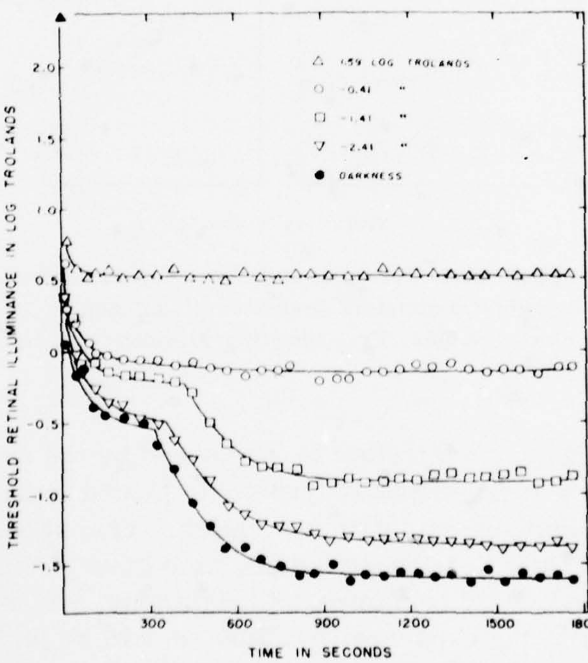


FIG. 3. Dark adaptation measured with difference threshold to dimmed lights (unfilled points) and with absolute threshold (black points). Preadapting luminance was 2.6 log trolands. Levels to which field was dimmed are shown on figure. (Hattwick, 1954)

But, instead of assessing sensitivity by a minimal detectable change, (a threshold), suppose it is assessed by a criterion of sensitivity which requires a fairly high level of visual function, well above the luminance thresholds. A good method is to use visual acuity to assess sensitivity. Then, a small or difficult acuity target would require a relatively high level of visual activity. In Fig. 4, one can see that dark adaptation curves look about as expected when an acuity object is used as a criterion of sensitivity. There are no rod-cone differences at high levels, and there is a general similarity to dark adaptation curves based on the two kinds of luminance thresholds.

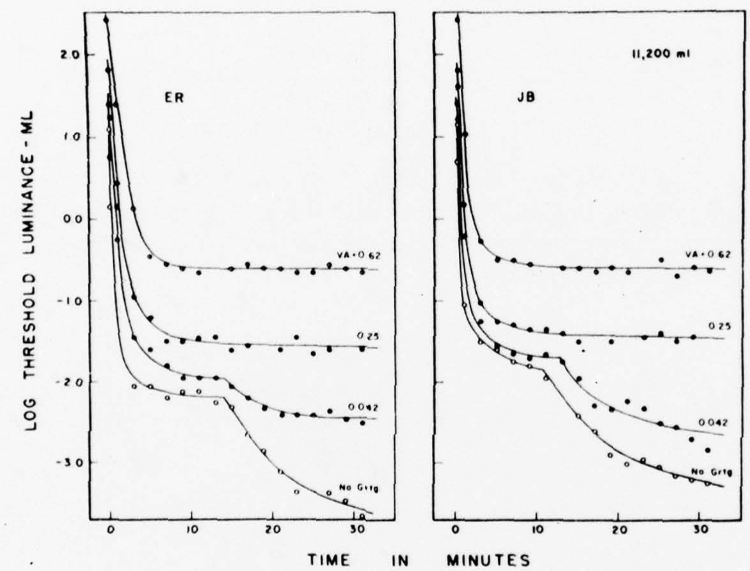


FIG. 4. Dark adaptation measured by log luminance necessary to achieve constant levels of visual acuity using grating acuity object. Pre-adapting luminance is indicated. (Brown, 1954)

Finally, let dark adaptation be measured by the change in luminance of a supra-threshold stimulus judged to have constant subjective brightness—a "memory match." One should expect less and less light to be required, as time goes on in darkness, to match a particular remembered brightness, and, in the upper curve of Fig. 5, the expectation can be seen to be justified.

To summarize: when the increase of visual sensitivity in dark adaptation is measured a consistent picture emerges. Whether the eye is in darkness or in dimmed light, whether judging brightness or discriminating a pattern, the picture is

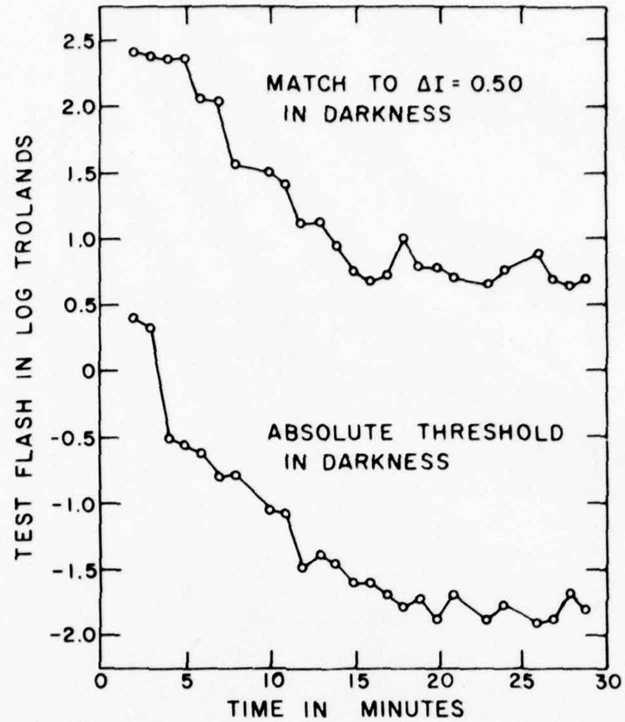


FIG. 5. Comparison between absolute threshold dark adaptation curve and dark adaptation measured by memory match. Upper curve shows retinal illuminances which maintain constant apparent brightness in test flash which has value of 0.50 log trolands after complete dark adaptation. (Florida State Univer. Laboratory)

one of increasing sensitivity during dark adaptation. Sensitivity changes can be predicted, at least generally, from one variable to another, and sensitivity appears to be serving its purpose as an explanatory concept.

Sensitivity during Light Adaptation

When one tries to measure sensitivity at times in which the sensitivity is being decreased in light adaptation, on the other hand, a disturbingly complicated pattern results. The course of light adaptation seems to depend entirely on the way one measures sensitivity.

If one uses the effect of light in raising the absolute threshold, light adaptation appears to be the opposite of dark adaptation. It seems to be a process of continuous sensitivity loss which takes about ten minutes or so to complete. Fig. 6 shows this familiar and reasonable pattern.

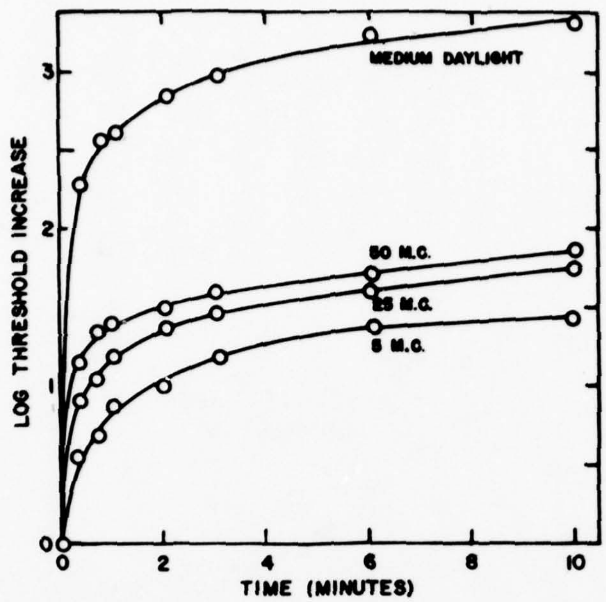


FIG. 6. Light adaptation measured by first absolute threshold of dark adaptation as function of duration of light adaptation. (Lohmann, 1906)

But if one uses the difference threshold to measure sensitivity, light adaptation takes a very different form and time course. It seems to be completely unpredictable from the absolute threshold data. The sensitivity loss is immediate in Fig. 7, which shows the beginnings of light adaptation, and the early loss is followed by a slow, small oscillation of sensitivity (see Fig. 8), over just about the period over which the absolute threshold method showed a smooth, continuous sensitivity decrease.

Apparently, the oscillation picture emerges again when one uses visual acuity for the measurement. Some years ago, in a personal communication to the author, Col. Anthony Debons said that he had investigated the course of light adaptation using visual acuity as his sensitivity measures. Although he apparently never published his results, he indicated that the picture of light adaptation which he obtained was in all respects like that obtained with the difference threshold. Immediately after the adapting light was turned on, much light was required to see a given acuity pattern, representing a sudden sensitivity loss. As light adaptation progressed, less light became necessary, reaching a minimum after a few minutes, then drifting upward just as do the curves of Fig. 8.

An additional problem appears when one uses a supra-thresh-

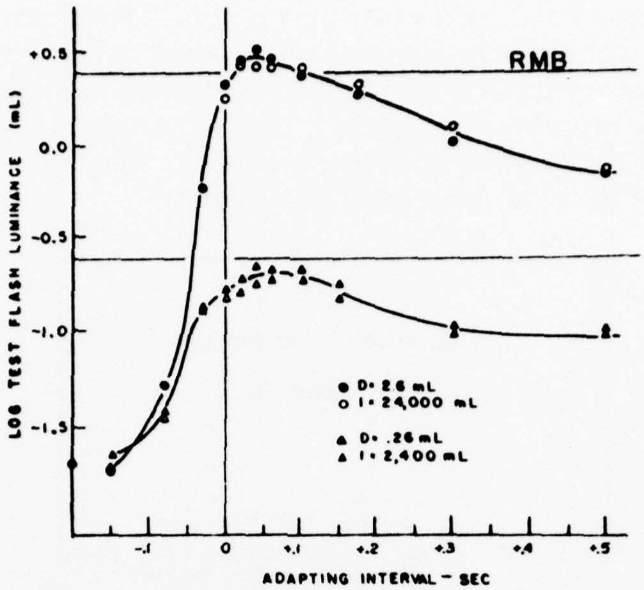


FIG. 7. Early light adaptation showing transition from absolute threshold to difference threshold against adapting light. (Boynton, Bush, & Enoch, 1954)

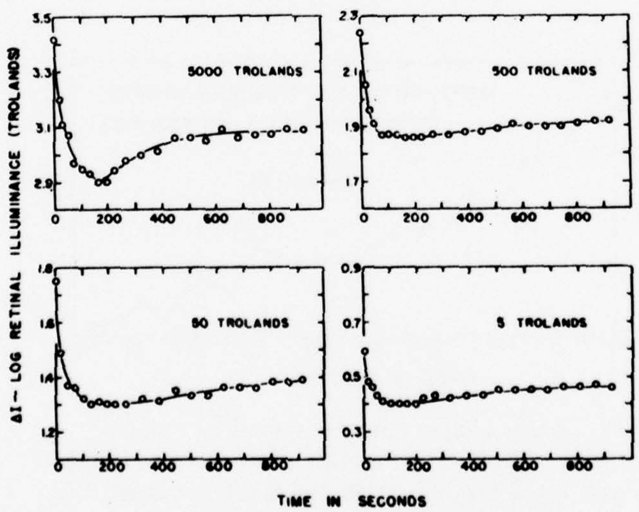


FIG. 8. Later light adaptation measured by difference threshold to adapting light. (Baker, 1949)

old criterion to measure sensitivity during light adaptation in order to have a comparison with the dark adaptation curves of Fig. 5. The amount of luminance necessary to match a remem-

bered, high level of brightness looks a bit like the difference-threshold curve, but is much extended in time. Fig. 9 and 10 compare the difference-threshold light adaptation curve with the curve obtained when the test stimulus is adjusted to match the remembered, apparent brightness it had in the dark-adapted state, before the adapting field was turned on. The continuous long drift of Fig. 10 is completely anomalous.

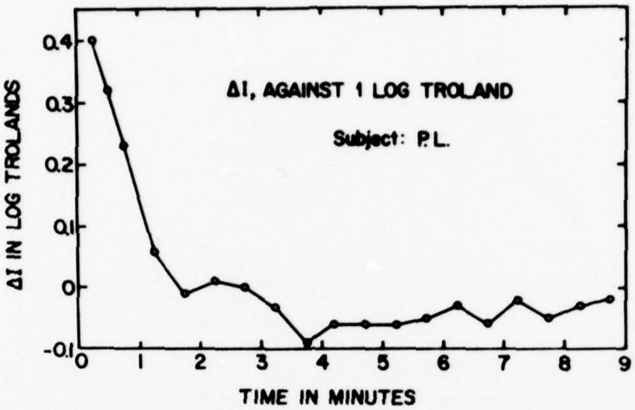


FIG. 9. Difference-threshold light adaptation in one subject for comparison with Fig. 10. (Florida State Univer. Laboratory)

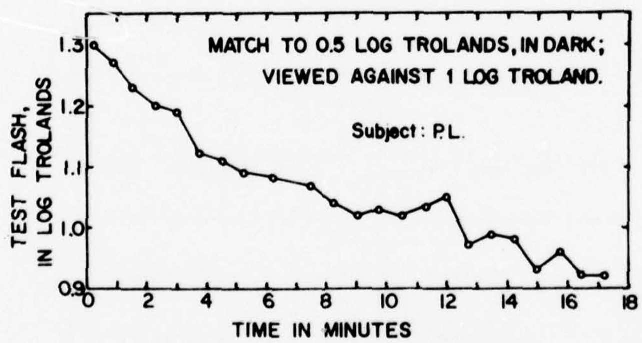


FIG. 10. Light adaptation measured by retinal illuminance required to match remembered brightness of 0.5 log troland stimulus flash presented in dark just before light adaptation. (Florida State Univer. Laboratory)

A further method of measuring sensitivity is available for light adaptation: matching apparent brightness. Sensitivity can be measured by comparing the luminance of a light-adapting

area of the retina with the luminance necessary to match its subjective brightness in a dark-adapted area of the retina. The dark-adapted area is usually in the other eye to avoid the effects of stray light from the light-adapting region. The result, which can be seen in Fig. 11, is a picture qualitatively in agreement with the absolute threshold picture, but, quantitatively, it is in agreement with nothing else. Its time scale is intermediate between those of the absolute threshold curves and the difference-threshold curves.

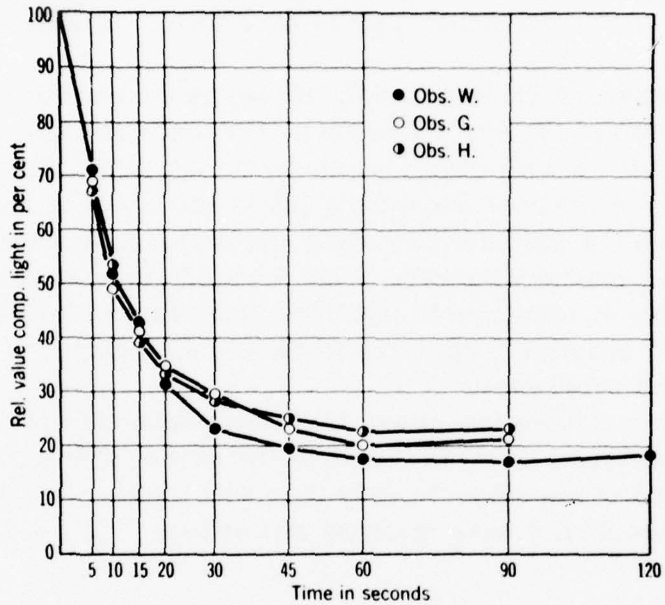


FIG. 11. Light adaptation measured by comparison light technique. Plotted is relative luminosity of measuring light in dark-adapted eye which is required to match light-adapting area in other eye. (Geldard, 1953)

To summarize: the different measures of sensitivity which yielded such a consistent picture of dark adaptation yield various complex results during light adaptation.

Conclusions

Sensitivity is a concept which is useful only in a limited way. Sensitivity can be used as an explanatory term to understand the way the subject acts, but only as long as he is in circumstances where his sensitivity either is considered to be constant, or is increasing in dark adaptation.

As soon as the subject enters conditions in which sensitivity will ultimately be lost, i.e., in light adaptation, the rules for comparing the different measures of sensitivity no longer hold. It becomes crucial to know what kind of a task the subject is expected to perform. At the present state of information, it would appear that at least three kinds of sensitivity are involved during light adaptation.

1. Sensitivity against glare (as in difference-threshold discrimination, or in visual acuity tasks). This kind of sensitivity shows a sudden loss during light adaptation, and a subsequent, minor oscillatory character, requiring several minutes to reach equilibrium.

2. Brightness-matching sensitivity (as in comparisons between different areas of the eye which have different exposure histories). This sensitivity is lost within a minute during light adaptation.

3. Ability to recover sensitivity (as in the effect of an adapting light upon the absolute threshold and dark adaptation). This sensitivity is lost most slowly of all during light adaptation. Many minutes of exposure to light are necessary before the subsequent dark adaptation curve reaches a stable shape, unaffected by more light adaptation.

It seems desirable therefore, that discussions of night vision should be cast first of all in terms of the nature of the visual task expected of the subject. Only then will measurements of his visual sensitivity have meaning and utility.

REFERENCES

Baker, H. D. The course of foveal light adaptation measured by the threshold intensity increment. J. opt. Soc. Amer., 1949, 39, 172-179.

Boynton, R. M., Bush, W. R., & Enoch, J. M. Rapid changes in foveal sensitivity resulting from direct and indirect adapting stimuli. J. opt. Soc. Amer., 1954, 44, 56-60.

Brown, J. L. Effect of different preadapting luminances on the resolution of visual detail during dark adaptation. J. opt. Soc. Amer., 1954, 44, 48-55.

Hattwick, R. G. Dark adaptation to intermediate levels and to complete darkness, J. opt. Soc. Amer., 1954, 44, 223-228.

Hecht, S., Haig, C., & Chase, A. M. The influence of light adaptation on subsequent dark adaptation of the eye. J. gen. Physiol., 1937, 20, 831-850.

Geldard, F. The human senses. New York: John Wiley & Sons, Inc., 1953. P. 39.

Lohmann, W. Ueber Helladaptation. Z. Sinnesphysiol., 1906, 41, 290.

VISUAL FIELDS

Ailene Morris, Chairman

INTRODUCTORY STATEMENT
by the Chairman of the Section

Ailene Morris
Institute of Visual Sciences, Presbyterian Medical Center
San Francisco

One important aspect of visual function is the sensitivity and extent of the visual field. However, the "perfect," or "normal" visual field is difficult to define. Before one can establish and scale grades of visual field decrement, one must define what is "normal". It is well known that the field varies greatly, whether tested under photopic or scotopic illumination conditions, whether the test object is a simple spot, an acuity target, or a colored target, and whether static or kinetic test-procedure is used. Certain characteristics of the visual field change from time to time, and can be assessed only after controlled, adaptation periods. Furthermore, the accuracy of the field measurement is only as good as the subject's ability to control his fixation locus.

A defect or decrement in the visual field could result in a lesser capability which affects visual performance. Field defects typically take the form of (a) a contraction of the extent of the field, (b) a depression in sensitivity, both general and localized, across the retina, or (c) the development of scotomata. These defects vary in degree of severity and specific locus, and the significance of the decrement depends on the particular case. For example, a minute scotoma in the central fovea could mean blindness, whereas the same scotoma in the far periphery might be of no consequence, unless the person is required to perform night visual search wherein the full, peripheral function is necessary.

Is it possible to establish grades of visual field decrement? This is certainly not the relatively simple job as would be the case with visual acuity, wherein the loss of one letter-line or

one decimal-unit of acuity means loss of retinal resolution of known and measureable degree.

As mentioned earlier, the relative importance of the various visual functions must be established to provide the basis for determining the priority of testing order. With high, photopic acuity and normal color-vision recorded for a subject, one can assume a good, central visual field and not have to measure it. A measurement of high intraocular pressure, suggestive of glaucoma, would lead one to check the field more carefully for the possible associated defects.

In this section on Visual Fields, Dr. Milton Flocks discusses Clinical Measurements, including various screening methods, perimetric techniques, and machine-testing. His work with Harrington on clinical perimetry and the development of the Harrington Screener well qualify Dr. Flocks to cover this area.

The Laboratory Measurement of Visual Fields is presented by Dr. Richard Copenhaver. His work in the use of computer-averaging techniques for the sensitive determination of retinal activity is outstanding in the recent advances in this area of research. By employing laboratory methods for quantitative measurement of response to weak signals at various retinal locations, visual field maps can be achieved which dramatically reflect minimal flaws and decrements. As exotic as these laboratory techniques seem to be at present, they may well become the practical solution for objective, rapid, and efficient assessment of the visual field.

CLINICAL MEASUREMENT OF THE VISUAL FIELDS

Milton Flocks
School of Medicine
Stanford University

This paper is directed toward the stated objectives of this meeting of the Armed Forces-NRC Committee on Vision.

1. To define perfection in each visual parameter, (here the visual fields), "to quantify the decrements from perfection when feasible," and, if possible, to divide the defects into ten decrements of function.

2. "To discuss the best ways of measuring the specific visual function, as well as to suggest the most practical method suitable for screening techniques by lay personnel," with special reference to automatized machine techniques.

3. To make comments concerning the amenability of the function to improvement by training, and the predictability of decremented change of the function with age.

Definitions

The visual field of an eye may be defined as that portion of space in which objects are visible to that eye while it is fixating on a single point. A field defect is a disorder of the visual system; and, as such, every effort must be made to uncover its cause, for the individual's vision and even his life may depend on finding the basis for the defect. Therefore, whenever a field defect is uncovered a complete, ophthalmologic examination is in order.

It is useful to define and differentiate the peripheral field, the central field and central vision.

The normal, monocular visual field as defined by Harrington (Harrington, 1956), is a "slightly irregular oval which measures, from fixation, approximately 60° upward and 60° inward, 70 to

75° downward and 100 to 110° outward." The visual field of the two eyes together is a combination of the right and left monocular fields which extends about 200° laterally and 130° vertically, and contains a large central area which is viewed with both eyes. The binocular visual field is that area of the field of the two eyes together which is seen by both eyes at the same time, and is about 120° in lateral extent and about 120° in vertical extent. The peripheral field is the same as the normal, monocular visual field, except that the central 3°-5° from fixation is excluded. The central field is that portion of the monocular visual field within 25° from fixation. Central vision is a description of central visual acuity and determines the integrity of the visual field of the central 2°. It is quite different from the central visual field.

In measuring visual fields, the monocular peripheral fields and the central fields of each eye separately are the only tests ordinarily made.

Perfect visual fields are normal visual fields, both monocularly and binocularly. As has already been stated, anything other than perfection is abnormal, and must be investigated and defined. The field defects may also be divided into progressive and non-progressive defects. If the defect is of a progressive nature then treatment should be instituted, and the patient disqualified.

Those visual fields defects which are stationary or non-progressive in nature, such as those due to an old injury, or old inflammatory chorioretinal scar, can be separated into decrements or degrees of impairment of visual function.

Decrements

The following 10° of functional, visual field loss are listed in order of degree of impairment. This division into degrees of functional impairment is arbitrarily arranged by the author, and to his knowledge, this is the first time such a division has been suggested. If such a division into decrements proves useful, it probably will be improved.

1. Normal visual fields in both eyes with binocular vision (simultaneous macular perception).

2. Normal visual field and good vision in each eye without binocular vision (simultaneous, macular perception).

3. Small scotoma in one eye outside of 20° and inside of 60° on the nasal side (in the area overlapped by the other eye).

4. Small scotoma in one eye outside of 20° and inside of 60° on the temporal side (in the area overlapped by the other eye).

5. Small scotoma either eye within 10°-20°.

6. Small scotoma either eye inside of 10°.

7. Bjerrum scotoma, or sector defect in one eye.

8. Large, field defects of any type in one eye, or blindness in one eye.

9. Hemianopsias.

10. Absolute blindness - both eyes.

Field defects can be described qualitatively as well as quantitatively. The nature or name of the defect is important because it suggests the etiology of the disorder and also hints as to the degree of functional impairment. Thus, hemianopsias, ring scotomas, Bjerrum scotomas, and sector defects should, probably, always disqualify an individual for flying, regardless of how small the defect is.

Testing the Visual Fields

The three principal, standard methods of testing the visual field which are in current use are the tangent screen for testing the central field, the arc perimeter, and the Goldmann or hemispheric perimeter for testing the peripheral fields. Any standard textbook of perimetry (Harrington, 1956; Traquair, 1948) describes the methods used in detail.

Two aspects of the central field are of particular importance: (a) ninety-five per cent of field defects can be picked up by examination of the central field; (b) from a functional standpoint, defects in the central field are far more important than those in the peripheral field outside of 20° from fixation. From a practical standpoint, central field-testing is more sensitive and more important than peripheral field-testing.

Visual Field-Screening

Visual field-screening can be done by the confrontation technique with the examiner using his own finger as a test object between his eye and the patient's eye. However, beyond question, the Harrington-Flocks Multiple Pattern Method of visual field-screening is the best way in current use to achieve this objective (Danielson, 1956). It is designed to screen the great mass of people, but could easily be modified to test pilot-candidates so as either to make it more sensitive, or to have fewer false-positives, depending on the objective and needs. By simultaneously

stimulating more than one quadrant of the visual field, it utilizes the phenomenon of extinction to provide added sensitivity. The rapid exposure of the stimuli (0.25 seconds) prevents the patient from losing fixation and following a stimulus in the periphery. This apparatus and technique has been adequately described elsewhere (Harrington & Flocks, 1954; 1955). In addition, the apparatus could easily be automated so that a technician would not be necessary for the test.

Visual field function cannot be improved by training. Decremental change is not predictable, except to state that, as the individual becomes older, he is more likely to get one of the degenerative disorders which produces a field defect.

REFERENCES

Danielson, R. W. Relation of fields of vision to safety, trans. Amer. Ophthal. Soc. Driving, 1956, Vol. 54, 369-416.

Harrington, D. O. The visual fields. St. Louis: C. V. Mosby Company, 1956.

Harrington, D. O., & Flocks, M. Visual field examination by a new tachystoscopic multiple pattern method. Amer. J. Ophthal., 1954, 37, 719.

Harrington, D. O., & Flocks, M. Multiple pattern method of visual field examination. J. Amer. Med. Assoc., 1955, 157, 645-651.

Traquair, H. M. An introduction to clinical perimetry. (5th ed.) St. Louis: C. V. Mosby Co., 1948; London; Henry Kimpton, 1948.

ELECTROPERIMETRY: A LABORATORY METHOD FOR THE STUDY OF THE VISUAL FIELD

R. M. Copenhaver and N. W. Perry, Jr.
Colleges of Medicine and Health-Related Professions
University of Florida

The aim of perimetry has been described as "the quantitative examination of visual acuity in all portions of the visual field" (Harrington, 1964); however, "visual acuity" is a term usually reserved for the measurement of vision in the central part of the visual field. Particularly with ill or uncooperative patients, time is a factor which requires that the visual field be measured in a relatively crude manner, usually by the detection of moving test objects of different sizes. Quantitative perimetry, in its finest sense, requires standardization of all parameters of test stimuli, such as background illumination, intensity of stimulus, size, color of stimulus, and speed, or motion, of the test stimulus. In clinical practice these are rarely standardized, and for clinical purposes the presence of field defects, or scotomas, becomes more significant than generalized depressions of various isopters. The former contributes information about the locations of pathological lesions, whereas the latter are more difficult to distinguish from established norms because of questionable standardization of stimulus parameters, poor ocular fixation, variable accuracy of the patient's response, and variable reliability of the examiner in interpreting and recording the patient's response. Harrington has emphasized that "It is of the utmost importance to remember that perimetry is a subjective examination of the sensory pathways. That it frequently involves the analysis of a disorder in sensory perception, and is, therefore, open to all of the objections of any subjective test."

It was hoped that, through an electrophysiological approach, visual field-testing could become completely objective by eliminating the need for an interpretive response to the stimulus by

the patient, and a subsequent interpretation by the examiner of the examinee's response. It is the purpose here to summarize and review some of the progress which has occurred in this area, and the many problems that have arisen.

Adrian and Matthews (1934) described rhythmic changes in the electroencephalogram in response to flickering ocular illumination. This "photic driving" is best demonstrated with high-intensity, stroboscopic flashes located close to the eye, and a flicker frequency approximating the inherent rhythm of the electroencephalogram. Bartley (1935) recognized the important part played by stray light in stimulating large retinal areas, in producing photic driving and electroretinograms. The recording of occipital potentials evoked from the occiput, using such gross stimuli, has sometimes been useful in indicating the side of a cerebral lesion (Brazier & Barlow, 1956; Ellingson, 1960; Kooi & Bagchi, 1962; Vaughan & Katzman, 1964; Vaughan, Katzman, & Taylor, 1963).

In the past decade, elaborate electronic devices have been developed capable of extracting signals bearing an established relationship in time to the stimulus from other potentials which are not "time-locked," such as movement artifacts. Using electronic devices such as computers, small potentials evoked from the visual, auditory, and somatic sensory systems have been extracted from larger background potentials—noise (Barlow, 1957; Brazier & Barlow, 1956; Communications Biophysics Group-MIT, 1959; Goff, Rosner, & Allison, 1962). With conventional recording techniques, it was difficult to detect signals less than 20 microvolts (μv) from noise. Recently, 0.1 μv visual-evoked potentials have been detected and displayed using computers (Gouras, Armington, Kropfl, Tepas, & Gunkel, 1962). Light sources which flood the entire retina with light have generally been employed. The diffuse stimulation of these light sources has generally been recognized, as when using stroboscopic lights, or when stimulating through closed lids. Not uncommonly, however, smaller, high-intensity stimuli have been used where background illumination and the state of retinal adaptation are either uncontrolled or unspecified. It has long been appreciated that the use of such small light sources as test stimuli does not necessarily result in discrete retinal stimulation (Asher, 1951; Boynton & Riggs, 1951; Boynton, 1953; Crampton & Armington, 1955).

Copenhaver and Beinhocker (1963) employed small, flickering light stimuli with moderate background illumination to achieve relatively discrete retinal stimulation to test specifically the

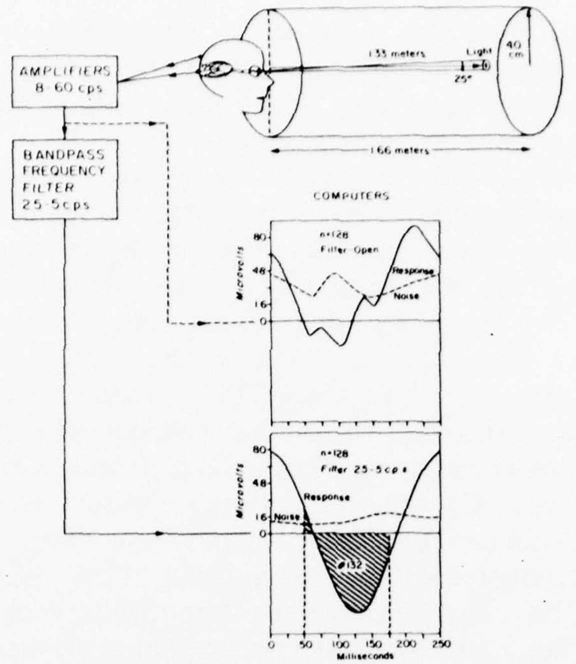


FIG. 1. Diagram indicating method of ocular stimulation, recording, and actual tracings of evoked responses obtained from computer. Area of filtered evoked response below base line between 50 and 175 milliseconds integrated to serve as quantitative measure of size of evoked response. "Noise" (dashed lines) representing averaged response with light visually occluded but clicking.

feasibility of objective visual field-testing. Evoked occipital potentials were recorded from two disc-electrodes placed on the skin and vertically oriented over the occiput. These potentials were amplified, passed through a narrow band-pass frequency-filter, and the area of each summed, evoked wave form between 50 and 200 milliseconds after the stimulus was integrated to give a digital response. Fig. 1 is a diagrammatic representation of the recording method. Either the single light subtending 2.5° of the arc could be moved to different points in the field, or fixation of the eye could be shifted for testing of different areas within the visual field. Twenty-five patients with visual field defects were tested, and, in the majority, field defects could be crudely detected by this method, corresponding to those obtained subjectively. Experiments were performed on normals to demonstrate that under optimal conditions the blind-

spot scotoma could also be detected. Actually, experiments utilizing the blind-spot scotoma were initially used to determine the intensity, size of stimulus, and the amount of background illumination necessary to achieve a degree of local retinal stimulation. It was felt that only in this way can one be relatively certain that stray light is not stimulating the visual system through retinal receptors, outside of the "blind" areas of a visual field, which would cause false-positive, evoked responses. This approach has sometimes been critized by arguing that, since fixation is often a problem, diffuse stimulation is more rational. Vaughan, Katzman, and Taylor (1963) reported that using full-field stimulation through closed lids and lateral electrode placements over the occiput, they are able to detect hemianopsias reliably by recording visual-evoked responses. However, the detection of smaller field defects cannot reasonably be expected with such techniques without recognition of the need for accurate fixation and the use of stimuli small enough to explore visual space. Certainly, the electrophysiological approach should initially be most useful where the patient is unable to respond, as when in coma, or when anesthetized. Under these circumstances, fixation by the subject is not possible. For such occasions, a fiber-optic ophthalmoscope has been proposed which could project a stimulus onto the retina under direct observation (Copenhaver & Perry, 1964). Such a device is now nearing completion in the laboratory at Florida State University. A skilled ophthalmologist should be able, with such a device, to stimulate almost any, desired, retinal location through a dilated pupil, and to maintain the stimulus with an accuracy of plus or minus 1° for the necessary time to record the visual-evoked response.

In addition to discrete retinal stimulation in detecting small scotomas, such as the blind spot, a narrow band-pass frequency-filter has been most helpful in reducing the number of averages necessary by enhancing the signal-to-noise ratio. Even without the use of an average-response computer, such narrow band-pass frequency-filtering has been used to separate signal from noise (Fricker, 1962). A criticism of this approach has been that, through such narrow-band frequency-filtering, the evoked response always necessarily has the configuration of a sine wave, and that valuable information is lost. However, the amplified, raw electroencephalogram can be recorded on tape to be studied at leisure, while the amplified, filtered, and processed evoked response may be observed "on line." The use of a tape recorder for storage of raw data has the advantage of allowing

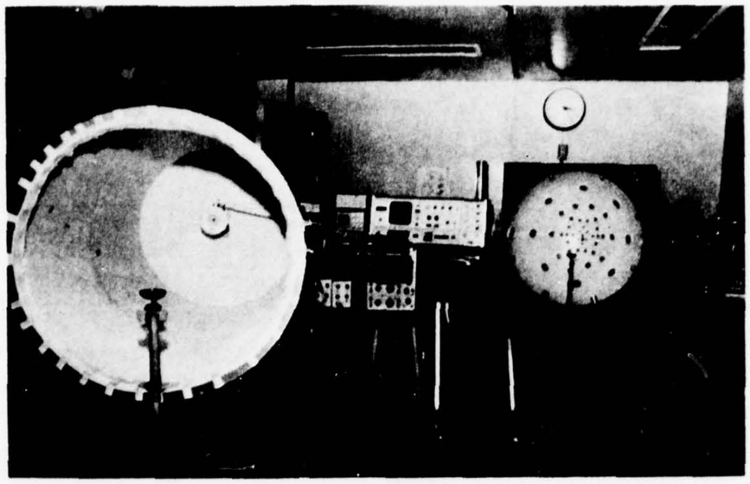


FIG. 2. Photograph of recording and stimulating equipment showing in left foreground cylinder with single movable stroboscopic light initially used in visual field experiments. New multilight stimulator on right to be used in future experiments. Display panel anterior and central to corner of multilight stimulator with series of lights corresponding to those in hemisphere. Computers in center background.

the same data to be restudied repeatedly, using different processing techniques.

The authors' are presently experimenting with a computer capable of sequentially flashing each of 45 Xenon stroboscopic lights embedded at different locations in a 1/2 meter-radius hemisphere (Fig. 2). After stimulation of each retinal point, the computer is capable of determining whether an evoked response has been obtained, provided the criteria for such a response have previously been inserted into the computer. Determination of the best criteria for recognition of an evoked response is a major problem receiving much attention. A light on a display panel, corresponding to the stimulus light in the perimeter, will then change to a color indicating that an evoked response has been obtained, or go out if an evoked response has not been obtained. The computer automatically clears itself, and then proceeds to the testing of the next retinal location until all 45 points have been tested, and the results are recorded on the display panel. Preliminary study suggests that at a stimulus frequency of 16 cycles per second (sec) only 64 averages may be necessary to separate evoked responses from "noise," when using the total, integrated area under the wave form as a measure of response

size. If further study confirms this, only 8 sec would be required at each test point. It is significantly easier to distinguish an evoked response obtained from macular stimulation, than from peripheral, retinal stimulation (Fig. 3). It is already apparent that a system of stimulation, employing test objects of fixed size and location, is an inflexible arrangement that does not allow the direction of adequate attention to the scotomatous area of the visual field. Little experience with this device allows no statement to be made, as yet, of its ability or reliability to detect visual field defects.

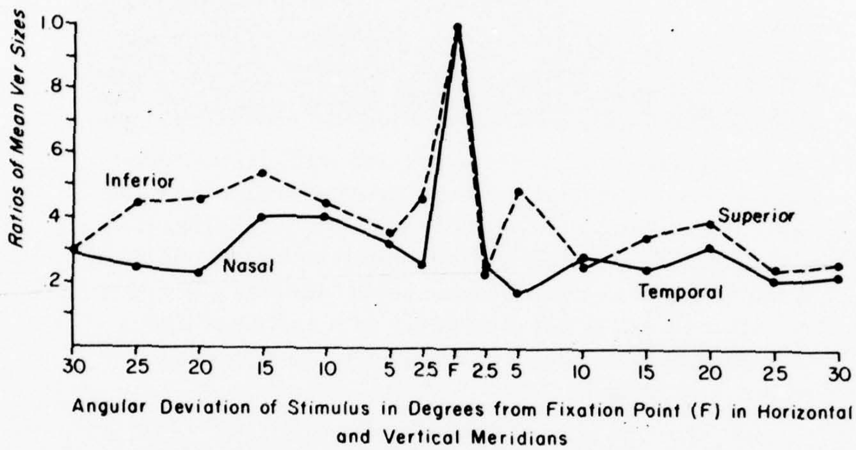


FIG. 3. Evoked occipital response shown when 2.5°-diameter stimulus light is located at different points in visual field of right eye of one trained observer. Each point represents mean of six trials (n = 128 flashes each trial) with all trials randomly recorded. Means plotted as ratios of peak response (fovea). Ver-visually evoked response.

As in many other laboratories, much of the time of the authors has been spent not in the study of subjects with visual defects, but in studies of various stimulus parameters, and other variables that may affect such responses.

A lack of knowledge about many characteristics of the complex, cortical-evoked responses has delayed the interpretation and, hence, the application of such recorded responses. For example, the study of wave configuration has yielded little concrete information about the significance of different components of the wave forms. The different components of the electroretinogram have been identified with both photopic and scotopic processes, even in dealing with the smaller, averaged responses (Gouras, Armington, Kropfl, & Gunkel, 1964). Few studies have

attempted to relate components of the visual-evoked, cortical response to photopic and scotopic processes (van Balen & Henkes, 1960). It has been established that the average evoked electroretinogram is primarily scotopic, although, with high rates of flicker and colored lights, photopic processes have been identified (Armington, Tepas, Kropfl, & Hengst, 1961). The cortical response appears to be primarily a photopic response as determined from study of spectral sensitivity curves (Armington, 1964), and dark adaptation. During the course of partial dark adaptation, Perry & Copenhaver (in press) found no consistent changes in the amplitude or shape of visual cortical responses, while the evoked electroretinogram increased markedly in amplitude. Therefore, it is difficult to relate any particular component of this wave to a scotopic process. In addition, high rates of flicker and orange lights favoring photopic processes have enhanced macular sensitivity in recording average evoked electroretinograms (Armington _et al_., 1961), quite comparable to that obtained with slow rates of flicker and white lights (effective scotopic stimuli) when recording evoked occipital responses (Fig. 3) (Copenhaver & Perry, 1964). This further suggests that the overall amplitude of the evoked occipital response is primarily representative of photopic processes. The difficulty in identifying scotopic components in the cortical-evoked responses may relate to the large representation of the macula in the visual cortex, directly underlying the recording electrodes.

The difficulty is further compounded by the marked variability in configuration of wave shapes caused by different electrode placements (Cobb & Dawson, 1960; Monnier, 1952), and among different individuals.

Nor is there agreement as to the origin of these potentials. Several studies suggested the earlier latency components are derived from primary, visual cortex (Ciganek, 1954; Vaughan _et al_., 1963), while other studies suggest that these responses probably arise from visual-association areas (Hill & Parr, 1963).

It was hoped that the electrophysiological approach would eliminate the subjectivity in present, clinical methods of recording the visual fields. Unfortunately, many of the same factors that make standard perimetry "subjective," such as lack of attention, habituation, and fatigue [Haider, Spong, & Lindsley, 1964; Perry & Copenhaver, in press (a)] also cause significant decrements in the amplitude of visual-evoked cortical potentials. There is even a suggestion that forced vigilance may enhance

such responses (Davis, 1964). Complex interactions may occur when different, sensory modalities are being concurrently stimulated (Brazier, 1964).

The cortical-evoked response is a complex wave showing much intersubject variation and, while fairly stable in the same subject to one set of stimulus parameters (Dustman & Beck, 1963), will vary with wave length, frequency, luminance, and location of the stimulus (Armington, 1964). Much difficulty undoubtedly arises from the fact that intervening tissues, such as skull and scalp, separate the generated, cerebral potentials from the recording electrodes. Thus, the potentials recorded from the scalp are only about 20 per cent as large as those recorded simultaneously from the cortex (Giblin, 1962), and the wave form is altered in shape as well as amplitude (De Lucchi, Garoutte, & Aird, 1962).

Some reports indicate that differences in evoked cortical responses between individuals are unrelated to differences in the electroencephalograms of these individuals (Dustman & Beck, 1963; Ebe, Aki, & Miyazaki, 1962), while others have associated some features of the evoked cortical response with various components of the electroencephalogram (Tepas, Armington, & Kropfl, 1962; Kooi & Bagchi, 1964).

Changes in pupil size affect the intensity of the stimulus reaching the retina and, therefore, may cause changes in the evoked response. Some studies have implicated changes in pupil size from attentional factors or habituation to alterations in evoked cortical responses (Fernandez-Guardiola, Harmony, & Roldon, 1964), while, in other studies, pupillary changes were not found responsible for such alterations (Garcia-Austt, Vanzulli, Bogaiz, & Rodriquez-Barrios, 1962).

If anesthetized patients are to be examined, another variable is the choice of anesthetic, since some anesthetics may cause decrements in the occipital responses (Domino, Corssen, & Sweet, 1963).

These problems and others such as artifacts from myogenic muscle potentials (Bickford, Galbraith, & Jacobson, 1963), and differences with age (Copenhaver & Perry, 1964) will, of course, require further investigation if control of such variables is to be achieved.

The evoked retinal response is more stimulus-dependent, better understood, and apparently little affected by the many extraneous factors which may alter the cortical evoked response (Copenhaver, Tepas, et al. 1962; Tepas & Perry, 1962, & Perry,

1964). However, because of the lack of sensitivity of this response (Tepas et al., 1962; Copenhaver & Perry, 1964), which requires the use of relatively intense light stimuli, focal, retinal responses appears to hold little potential for studies of the visual field, where anything but extremely gross resolution is desired. Nevertheless, computer techniques allow a sensitivity sufficient to detect relatively small areas of functioning retina (Gouras, Gunkel, & Jones, 1962), as in retinitis pigmentosa, where an evoked response may be detected while the field is absolutely constricted to within 3° of the fixation point (Gouras et al., 1962). Conversely, lesions of the central retina, which are several square millimeters in diameter, cause significant decrements in the visual-evoked retinal response (Gouras et al., 1964).

Such decrements from central retinal lesions have been crudely related to the degree of visual loss when recording at the occipital level (Copenhaver & Perry, 1964).

Recording of the evoked retinal response may then be of value in helping to distinguish retinal diseases from those located more posteriorly in the visual system, such as an optic nerve, tract, or radiation lesions (Ebe et al., 1962; Copenhaver et al., 1963; Gouras et al., 1964). Present, subjective testing of the visual field allows a three-dimensional interpretation of the location of a lesion. For example, it may assist in the localization of a lesion in the vertical and horizontal meridians of the visual system, as well as contribute information about its location in the anterior-posterior axis of this system. The recording of simultaneous, evoked retinal and cortical responses allows a kind of crude, fourth dimension by contributing objective information detected at different depths in the visual system.

In summary, the resolution of current methods of electroperimetry is extremely poor as compared to quantitative, visual field-testing by standard means in a cooperative patient. In addition, the complexity of the cortical response, which is poorly understood, the expense and complexity of the equipment required, and the sensitivity of the response itself to subjective variables promises to delay the entry of this exotic technique on the clinical scene. Nevertheless, the advent of new electronic techniques, which allow the recording of visual-evoked responses at the retinal and cortical levels of the visual system from more physiological light stimuli, has spurred study of the many variables which may affect these responses. Since such attempts are still in their infancy, there remains room for optimism. It is anticipated that, ultimately, electroperimetry will become more

economical and rapid than current methods of visual field recording, which require much of a physicians' or technicians' time. Computers are likely to become less expensive, less temperamental, and simpler to operate. More important, however, is that even if the electrophysiological approach cannot duplicate the resolution of subjective testing, it may yield information of significance about visual physiology, and information clinically useful which is unique to such methods.

REFERENCES

Adrian, E. D., & Matthews, B. H. C. The Berger rhythm: Potential changes from the occipital lobes in man. Brain, 1934, 57, 355.

Armington, J. C. Relations between electroretinograms and occipital potentials elicited by flickering stimuli. Doc. Ophthal., 1964, 18, 194-205.

Armington, J. C., Tepas, D. I., Kropfl, W. J., & Hengst, W. H. Summation of retinal potentials. J. opt. Soc. Amer., 1961, 51, 877-886.

Asher, H. The electroretinogram of the blindspot. J. Physiol., 1951, 112, 40P.

Balen, van, A. T. M., & Henkes, H. E. Recording of the occipital lobe response in man after light stimulation. Brit. J. Ophthal., 1960, 44, 449.

Barlow, J. S. An electronic method for detecting evoked responses of the brain and for producing their average waveforms. Electroenceph. clin. Neurophys., 1957, 9, 340.

Bartley, S. H. Importance of stray light in producing cortical responses in rabbit and reducing implicit time of potentials. Amer. J. Physiol., 1935, 15, 720.

Bickford, R. G., Galbraith, R. F., & Jacobson, J. L. The nature of averaged evoked potentials recorded from the human scalp. Electroenceph. clin. Neurophys., 1963, 15, 720.

Boynton, R. M. Stray light and the human electroretinogram. J. opt. Soc. Amer., 1953, 43, 442.

Boynton, R. M., & Riggs, L. A. The effect of stimulus area and intensity upon the human retinal response. J. exper. Psychol., 1951, 42, 217.

Brazier, M. A. B. A study of the variability of response to flicker: the influence of other sensory stimuli. Doc. Ophthal., 1964, 18, 221-237.

Brazier, M. A. B., & Barlow, J. S. Some applications of correlation analysis to clinic problems in electroencephalography. Electroenceph. clin. Neurophys., 1956, 8, 325-336.

Ciganek, L. The EEG response (evoked potential) to light stimulus in man. Electroenceph. clin. Neurophys., 1954, 6, 65-84.

Cobb, W. A., & Dawson, G. D. The latency and form in man of occipital potentials evoked by bright flashes. J. Physiol., 1960, 152, 108-121.

Communications Biophysics Group of Research Laboratory of Electronics, & Siebert, W. W. *Processing neuroelectric data*. Cambridge, Mass.: Technology Press of MIT, 1959.

Copenhaver, R. M., & Beinhocker, G. D. Evoked occipital potentials recorded from scalp electrodes in response to focal visual illumination. Invest. Ophthal., 1963, 2, 4, 393-406.

Copenhaver, R. M., Beinhocker, G. D., & Perry, N. W., Jr. Advances in ophthalmology. Proc. Symposium of Flicker and Second Sympos., ISCERG Doc. Ophthal., 1963. (Sept.)

Copenhaver, R. M., & Perry, N. W., Jr. Factors affecting visually evoked cortical potentials such as impaired vision of varying etiology. Invest. Ophthal., 1964, 3, 6, 665-675.

Crampton, G. H., & Armington, J. C. Area-intensity relation and retinal location in the human electroretinogram. Amer. J. Physiol., 1955, 181, 47.

Davis, H. Enhancement of evoked cortical potentials in humans related to a task requiring a decision. Science, 1964, 145, 182-183.

Dawson, G. D. A summation technique for the detection of small evoked potentials. Electroenceph. clin. Neurophys., 1960, 12, 663.

De Lucchi, M. R., Garoutte, W., & Aird, R. B. The scalp as an electroencephalographic averager. Electroenceph. clin. Neurophys., 1962, 14, 191-196.

Domino, E. F., Corssen, G., & Sweet, R. B. Effects of various general anesthetics on the visually evoked response in man. Anesthesia & Analguia, 1963, 42, 735.

Dustman, R. E., & Beck, E. C. Long-term stability of visually evoked potentials in man. Science, 1963, 142, 1480-1481.

Ebe, M., Mikami, Jr., Aki, M., & Miyazaki, M. Electrical responses evoked by photic stimulation in human cerebral cortex. J. exper. Med., 1962, 77, 352-372. (Japan)

Ellingson, R. J. Cortical electrical responses to visual stimulation in human infants. Electroenceph. clin. Neurophys., 1960, 12, 663-678.

Fernandez-Guardiola, A., Harmony, J., & Roldon, E. Modulation of visual input by pupillary mechanisms. Electroenceph. clin. Neurophys., 1964, 16, 259-268.

Fricker, S. J. Narrow-band filter techniques for the detection and measurement of evoked responses. Electroenceph. clin. Neurophys., 1962, 14, 411-413.

Garcia-Austt, E., Vanzulli, A., Bogaiz, J., & Rodriquez-Barrios, R. Influence of the pupillary muscles and other muscles upon habituation to photic stimulation in man. Electroenceph. clin. Neurophys., 1962, 14, 289.

Giblin, D. R. Comparison of evoked potentials from cortex and scalp in man. Electroenceph. clin. Neurophys., 1962, 14, 290.

Goff, W. R., Rosner, B. S., & Allison, T. Distribution of cerebral somatosensory evoked responses in normal man. Electroenceph. clin. Neurophys., 1962, 14, 697.

Gouras, P., Armington, J. C., Kropfl, W. J., & Gunkel, R. D. Electronic computation of human retinal and brain responses to light stimulation. Ann. N. Y. Acad. Sci., 1964, 115, 763-775.

Gouras, P., Armington, J. C., Kropfl, W., Tepas, D. I., & Gunkel, R. D. Evaluation of visual function in man by electronic computation of evoked potentials. New York, Proc. Conf. on Data Acquisition and Proc. in Bio. and Med., 1962.

Gouras, P., Gunkel, R. D., & Jones, J. Spatial differences in the human ERG. Invest. Ophthal., 1962, 1, 3, 333.

Haider, M., Spong, P., & Lindsley, D. B. Attention, vigilance, and cortical evoked potentials in humans. Science, 1964, 145, 180-182.

Harrington, D. O. The visual fields: a textbook and atlas of clinical perimetry, (2nd ed.). St. Louis: C. V. Morley Company, 1964.

Hill, D., & Parr, G. (Eds.) Electroencephalography: a symposium on its various aspects. New York: MacMillan Company, 1963. Pp. 119-122.

Kooi, K. A., & Bagchi, B. K. Recognition of deviant cerebral responses to single photic stimuli. Electroenceph. clin. Neurophys., 1962, 14, 287.

Kooi, K. A. & Bagchi, B. K. Observations on early components of the visual evoked response and occipital rhythms. Electroenceph. clin. Neurophys., 1964, 17, 638-643.

Monnier, M. Retinal, cortical, and motor responses to photic stimulation in man. J. Neuro. Physiol., 1952, 15, 469.

Perry, N. W., Jr., & Copenhaver, R. M. Differential cortical habituation with stimulation of central and peripheral retina. Percept. motor Skills, in press. (a)

Perry, N. W., Jr., & Copenhaver, R. M. Evoked retinal and occipital potentials during dark adaptation in man. Amer. J. Ophthal., in press. (b)

Tepas, D. I., & Armington, J. C. Properties of evoked visual potentials. Vis. Res., 1962, 2, 449-461.

Tepas, D. I., Armington, J. C., & Kropfl, W. J. Evoked potentials in the human visual system. Biolog. Prototypes & Synthetic Systems, 1962, 1, 13-21.

Vaughan, H. G., & Katzman, R. Evoked response in visual disorders. Sensory evoked response in man. Ann. N.Y. Acad. Sci., 1964, 112, 1, 305-319.

Vaughan, H. G., Katzman, R., & Taylor, J. Alterations of visual evoked responses in the presence of homonymous visual defects. Electroenceph. clin. Neurophys., 1963, 15, 737-764.

INTRAOCULAR TENSION

Elwin Marg, Chairman

CLINICAL MEASUREMENT OF INTRAOCULAR PRESSURE

Mansour F. Armaly
Department of Ophthalmology and University Hospitals
University of Iowa

Interest in intraocular pressure and in its clinical measurement rests mainly, if not exclusively, on the possible relationship between this parameter and visual function. An examination of the relevant evidence and opinions would be, indeed, essential for the proper characterization of the clinical significance of this measurement; however, such a monumental undertaking is beyond the scope of this presentation.

In open-angle glaucoma, a raised intraocular pressure level is, in general, associated with the typical, progressive loss of visual function which may end in blindness. It is this tragic association which is responsible for the interest in the clinical measurement of intraocular pressure with the hope that it will significantly improve detection and management of this disease. However, while this association may be true, in general, for the advanced stages of the disease, the characteristics of the early stages are far from being definitively established. Advanced, glaucomatous field loss has been known to occur in the absence of ocular hypertension, and normal visual function has been known to exist in the presence of marked ocular hypertension. This absence of correlation between intraocular pressure level, and the presence or future development of glaucomatous field loss led to the terms "physiologic" and "pathologic" levels of intraocular pressure (Friedenwald, 1949). However, by definition, such levels are not predictive in nature, but, rather, are retroactive; for, in any one individual, a certain pressure level is considered physiologic if it is not associated with glaucomatous field defect, and pathologic, if it is associated with such defect. Thus, instead of being useful in predicting the present

or the future status of visual function, a knowledge of this function is necessary to characterize the pressure level.

In the absence of a simple, cause-and-effect relationship, one next inquires as to whether different pressure levels signify different risks and probabilities of the future development of glaucomatous visual damage. Critical evaluation of available evidence reveals absence of reliable information in this respect. No definitive information is available which could permit one to state that individuals with high pressure levels either have glaucomatous field damage, or will inevitably develop this damage in the future, or are more likely to develop this damage than individuals with lower levels of intraocular pressure (Armaly, 1960; 1962 a). In the presence of normal visual fields, a pressure level has no empirically established, predictive value with regard to the future of visual function. Any implication in this respect is of the nature of opinion and is not an empirically established relationship.

"Physiologic" or "normal" pressure levels have been too often confused with frequent, and "pathologic" with infrequent. Thus, data collected from ill-defined samples were analyzed to determine levels of "normal" and "abnormal" intraocular pressure. This determination was done by arbitrarily equating "abnormal" with a certain level of frequency, say the 5 or 1 per cent level, such that pressure levels that are two or three standard deviations away from the mean value are considered "suspect" and "abnormal"; the intensity of the abnormality being directly commensurate with its distance from the mean, or its infrequency. This, of course, assumes that in the presence of normal visual function, high pressure levels are indicative of a threat to the future of this function; such an assumption has not been empirically validated.

Ingenious models have been suggested to explain the manner in which intraocular pressure produces field loss and to account for the marked variability of vulnerability among individuals (Armaly, 1962 b; Gaffner & Goldmann, 1955). These models introduce a vascular factor on which the intraocular pressure acts to produce ischemia of the nerve-fibre bundle and the resulting functional loss. These models have been, in general, verified by clinical observation and investigation (Harrington, 1959). Numerous investigators are attempting to assess this interaction in the individual subject with the hope of determining whether a certain pressure level is likely to be associated with

glaucomatous visual loss in the future. These attempts, however, are still at the investigative level.

It is the author's belief that in the final analysis, the significance of the measurement of intraocular pressure is intimately determined by therapeutic limitations. The only variable which can be modified in this respect is a raised intraocular pressure. Thus, in the presence of glaucomatous field loss, a raised intraocular pressure dictates active hypotensive therapy; the expectation being that its reduction will beneficially modify the course of the visual function loss. There is very little that one can do, therapeutically, for glaucomatous loss of visual field when it is not associated with high pressure.

Amid this background of inadequate information on the natural history of open-angle glaucoma, and under the oppressive pressure of the threat of blindness which it carries, the following practical guidelines have evolved. In the presence of glaucomatous field defect, a high pressure level should be energetically counteracted with hypotensive therapy. A treatable pressure level, in this respect, may be as low as 20 millimeters of mercury (mm Hg). In the absence of glaucomatous field defect, such levels indicate a closer follow-up once every three to six months in order to follow visual function carefully for the earliest evidence of glaucomatous damage, which will then dictate hypotensive therapy. Some feel that pressure levels of 30 mm Hg, or more, should be treated, even when evidence of visual damage is absent.

It is of the utmost importance to realize the limitations of ocular pressure measurement as a preventive measure in glaucoma detection. More important is to transfer this knowledge accurately to the individual subject or patient. Glaucoma and its blindness are, in this respect, too well known by the general population. The limitations of pressure measurement should be clearly explained in order to avoid the development of harmful reactions, such as a false sense of security, or an unwarranted scare of glaucomatous blindness.

Within the above formulation of the problem, the clinical value of routine, ocular pressure measurement becomes readily apparent. For, using arbitrary guidelines of pressure levels, one may expect to divide the population into two groups on the basis of intraocular pressure measurement: Group I, with low pressure levels, constitutes the group for which there is little or nothing to offer therapeutically in the event that a glaucoma-

tous field defect is present. Group II, with high pressure levels, constitutes the potentially treatable group, and includes those cases in which definite therapeutic intervention is indicated in the event a glaucomatous field defect is present.

Thus, pressure measurement in this manner will uncover cases of treatable glaucoma that would have otherwise remained undetected until a very advanced stage of the disease, and only after permanent loss of considerable visual function. It should be emphasized, however, that in this manner, only a fraction of individuals with treatable glaucoma is detected. Even when a pressure level of 20 mm Hg is used as a criterion, 40 to 50 per cent of treatable glaucoma are missed by single pressure measurement (Armaly & Becker, 1961). In these cases, a treatable pressure level is demonstrable only on repeated measurement and follow-up. This realization is extemely important in determining interpretation and advice following a single determination of intraocular pressure.

It should be added, however, that all cases of treatable glaucoma will be detected by visual field examination. Thus, a great improvement in the yield of detection of treatable glaucoma can be achieved by the routine examination of central visual fields. This test will detect all those with glaucomatous field defect; such subjects are then thoroughly examined and followed up by pressure measurement to determine whether they are treatable or not.

To help obtain an idea of the size of the problem at hand, the findings are briefly summarized of a study of 2400 subjects over the age of 21 years who, to the best of their knowledge, had normal eyes (Armaly, 1965). These subjects received a complete eye examination, including applanation tonometry and central visual field examination. They came from different income levels and occupations, and were representative of the population of the city of Des Moines, Iowa.

Preliminary examination revealed that this sample cannot be considered as a homogeneous group having a single Gaussian distribution of applanation pressure. This hypothesis had to be rejected at the 1 per cent level of confidence. The distribution was markedly skewed to the right, such that using the statistics of a single Gaussian distribution will markedly underestimate the frequency of high applanation pressure.

Further analysis revealed that age and sex are significant factors in this respect, such that each age and sex group may be described as a homogeneous, single Gaussian distribution,

TABLE 1. The Average and the Standard Deviation of Applanation Reading

Age in Years	Males	Females	Percentages
20-29	14.93 ± 2.47	14.97 ± 2.51	11.9
30-39	15.17 ± 2.97	15.13 ± 2.82	18.0
40-49	15.55 ± 2.96	15.71 ± 3.04	< 0.006
50-59	15.89 ± 3.21	16.47 ± 2.89	< 0.006
60-69	16.33 ± 3.80	16.79 ± 3.79	< 0.006
70-79	16.14 ± 4.15	17.15 ± 3.83	6.28

but that different groups have significantly different statistics (Table 1). Both males and females show a progressive increase of pressure with age. Furthermore, after the age of 40 years, females show a significantly higher pressure than males. If a pressure of 20 mm Hg or more is used as a criterion for clinically significant pressure level, then it is evident that this portion will become greater with age, and it will be more in females than in males. Interesting, in this respect, is that this fraction increases exponentially with age at the same rate in males as in females (Fig. 1). If the sample frequency in different age and sex groups is now used to calculate the expected number of individuals with a pressure of 20 mm Hg or more in the United States, it is found that the total number is, indeed, startling (Table 2), coming close to 16 million individuals. Keeping in mind that cases of known, open-angle glaucoma and those with ocular complaints were excluded from this sample, it becomes evident that the calculated value represents a minimum estimate.

In conclusion, although understanding of the relationship between intraocular pressure level and visual function is far from being complete, or even adequate, and the present level of control of disease states involving these parameters is far from being satisfactory, nevertheless, a good part of the problem remains the detection of treatable cases of glaucoma. This is especially important because of the virtually symptomless nature of open-angle glaucoma. Routine measurement of intraocular pressure will significantly improve the extent to which treatable cases are detected and brought to medical attention. This yield can be markedly improved by including, in addition, an examina-

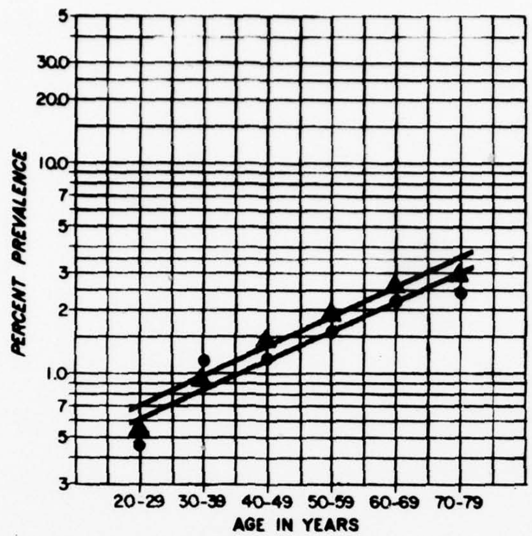


FIG 1. Percentage of frequency of individuals with applanation reading of 20 or more in different age groups of both sexes. Solid circles (males), solid triangles (females). Abscissa denotes age groups in years. Ordinate: logarithmic scale of percentage of frequency. Most secure points are those for age group between 40 and 69 years, due to size of sample. Line can be drawn to all points without significant deviation of any one point. Note parallelism of two lines and greater frequency in females.

TABLE 2. Frequency of Applanation Reading of 20 or More

	Males		Females	
Age in Years	Percentage of Ind. in Sample	Estimated Minimum* No. of Individuals in U.S. Population**	Percentage of Ind. in Sample	Estimated Minimum* No. of Individuals in U.S. Population**
20-29	4.5	501,000	5.5	611,000
30-39	11.2	1,351,000	9.4	1,655,000
40-49	11.5	1,295,000	13.8	1,603,000
50-59	15.7	1,418,000	19.3	1,813,000
60-69	21.8	1,390,000	25.4	1,818,000
70-79	23.7	865,000	28.9	1,283,000
Total		6,820,000		8,783,000

*Actual number in U.S. Population will be larger since cases of known glaucoma were excluded from this study.

**To the nearest 1,000.

tion of the visual field. A proper understanding of the arbitrary nature of this performance, and the correct information of the subjects about the meaning of a pressure measurement can markedly reduce the harmful effects that could otherwise result from the improper interpretation of clinical measurement of intraocular pressure.

REFERENCES

Armaly, M. F. Lessons to be learned from a glaucoma survey. J. Iowa State med. Soc., 1960, 501. (Aug.)

Armaly, M. F. Glaucoma tests: a population study. Sight-saving Rev., 1962, 32. (a)

Armaly, M. F. The vascular bed of the retina and optic nerve head. Int. Ophthal. Clin. The retina. Vol. 2. Boston: Little, Brown and Company, 1962. (b)

Armaly, M. F. On the distribution of applanation pressure: I. statistical features and the effect of age, sex and family history of glaucoma. Arch. Ophthal., 1965, 73, 11.

Armaly, M. F. & Becker, B. Tonometry and population screening: a symposium. New York: Nat. Soc. on prevention of Blindness, 1961.

Friedenwald, J. S. Symposium: primary glaucoma: I. terminology, pathology, and physiological mechanisms. Trans. Amer. Acad. Ophthal. otol., 1949, 53, 169.

Gaffner, F., & Goldmann, H. Experimentelle Untersuchungen über der Tusa wen hang vou augur dweksteigeneug eiud Gesichtsfeld schdigung. Ophthal., 1955, 130, 357.

Harrington, D. O. The pathogenesis of the glaucoma field: clinical evidence that circulatory insufficiency in the optic nerve is the primary cause of visual field loss in glaucoma. Amer. J. Ophthal., 1959, 47, 177.

INSTRUMENTS FOR MEASUREMENT OF INTRAOCULAR PRESSURE[1]

Robert A. Moses
Department of Ophthalmology and the Oscar Johnson Institute
Washington University School of Medicine

So far as vision is concerned, the intraocular pressure must be somewhat above atmospheric pressure for the soft leather eyeball to maintain its shape. If the intraocular pressure becomes too high, the eye loses vision, a syndrome which is clinically called glaucoma. No one knows where to draw the borderline between safe and unsafe intraocular pressure. Moreover, speaking of intraocular pressure is almost like speaking of the light intensity as one drives through a wooded area. Intraocular pressure varies with blood pulse, respiration, position (whether erect or recumbent), time of day, and so on.

Pressure is defined as force per unit-area. Any estimate of intraocular pressure must, in some way, be based on estimates, direct or indirect, of force and area. Intraocular pressure, P_O, is the result of aqueous secreted into the eye at rate F, escaping through a leak, or facility, C, into blood veins at pressure P_V.

$$F = (P_o - P_v) C$$

The common laboratory technique of cannulation of the eye and measurement of pressure with a manometer as not germane to this discussion, except as a method for calibration of other measuring devices. Such measuring devices, or tonometers, must necessarily measure intraocular pressure through the wall of the eye. Since the cornea is of relatively uniform structure, measurement at the cornea may be expected to give more uni-

1. This research has been supported by Grant NBO-3639-03 from the National Institute of Neurological Diseases and Blindness, National Institutes of Health, Public Health Service, Bethesda, Maryland.

form results than elsewhere, where the tonometer will rest over conjunctiva, sclera, and ciliary body, or choroid and retina. Only corneal tonometry is discussed in this presentation.

Classically, tonometers are divided into applanation and indentation types. Applanation tonometers may be divided into those in which fixed force is used and the area of contact between tonometer and cornea is measured, and those in which the force necessary to flatten a fixed area is measured. The fixed-force type of applanation tonometer is exemplified by the Maklakow tonometer which has changed little from its introduction in 1885. Fig. 1 shows one of these tonometers. A thin coat of dye is smeared on the end of the weight. After the weight is lowered on the anesthetized cornea of the supine subject, the diameter of the disturbed area of dye is measured and, since force and area are known, pressure is defined. Tears disturb the dye as well as corneal contact, so a wet eye will appear to have a lower pressure than a dry eye.

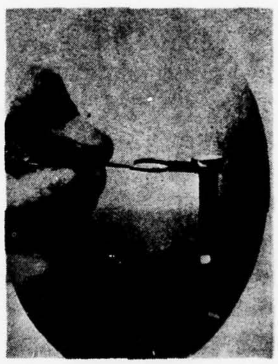


FIG. 1. Maklakow tonometer. Dye smeared on flat surface of tonometer is disturbed when tonometer is lowered onto cornea. Diameter of imprint is measure of intraocular pressure—larger imprint, lower pressure.

The modern descendent of the Fick (1888) fixed-area, variable-force tonometer is the Goldmann tonometer (Fig. 2). The fluorescein-stained tear meniscus surrounding the area of applanation defines that area. When the circle of applanation is viewed by blue light through a field-splitting prism two fluorescent arcs are seen. The force of the prism against the cornea is varied until the inner edges of the arcs index, indicating standard applanation diameter (Fig. 3). At 3.06 millimeters (mm) diameter, the force required to bend the cornea is balanced by the surface tension of the tears (Fig. 4).

The Goldmann tonometer, largely because of its beautiful theoretical development, has become the standard against which other tonometers are gaged.

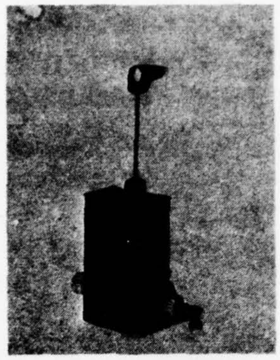


FIG. 2. Goldmann applanation tonometer. Used in conjunction with slit-lamp microscope. Force with which prism, above, bears against cornea is varied by knob, below.

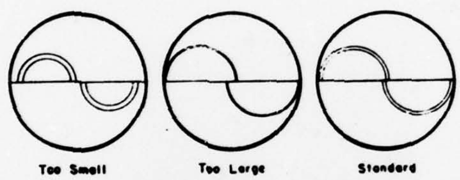


FIG. 3. Fluorescein-stained tear-meniscus as seen through prism of Goldmann applanation tonometer. Prism displaces half-fields 3.06 mm. When inner borders of semicircles are in line, applanation diameter is 3.06 mm.

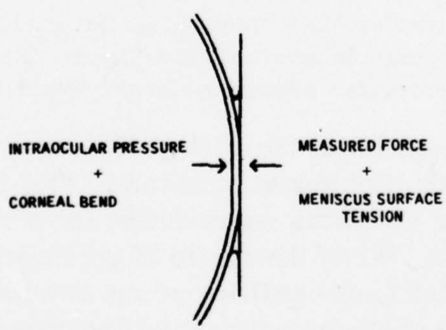


FIG. 4. Diagram of forces involved in applanation tonometry. At equilibrium force pushing prism toward eye, plus meniscus surface-tension pulling prism toward eye equals force of intraocular pressure over area of contact plus spring force of bend in cornea.

Other applanation-type tonometers are the Mackay-Marg, and that made by Block Engineering, Inc. These both record on a paper strip. The Mackay-Marg records the deflection of a stiff spring on which a small, central plunger is mounted (Fig. 5).

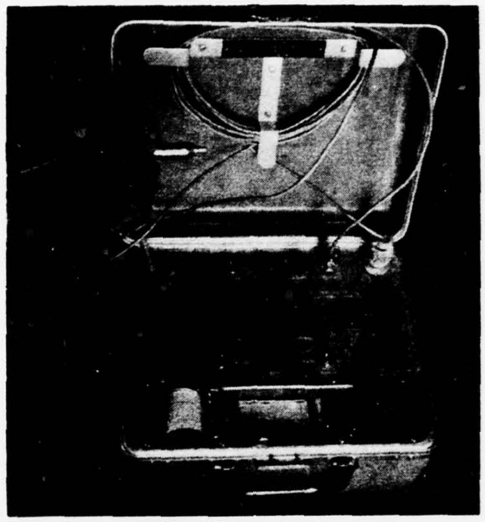


FIG. 5a. Mackay-Marg tonometer.

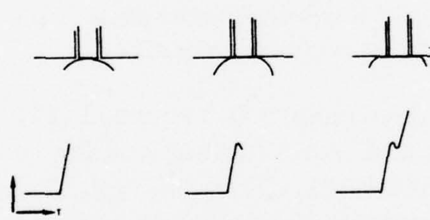


FIG. 5b. Relation of extent of contact between cornea and Mackay-Marg probe to recorded plunger deflection.

As the probe is advanced toward the eye, the plunger first supports intraocular pressure plus the corneal bending force. When the bend in the cornea passes over to the footplate the relief from this force is registered as a dip in the plunger-displacement record; now the plunger supports only intraocular pressure. This tonometer is so rapid that it may be touched to the unanesthetized cornea before the subject blinks.

The Block tonometer exerts gas pressure against a membrane applied to the eye. When the pressure is sufficient to balance intraocular pressure a shift in membrane position and a flex,

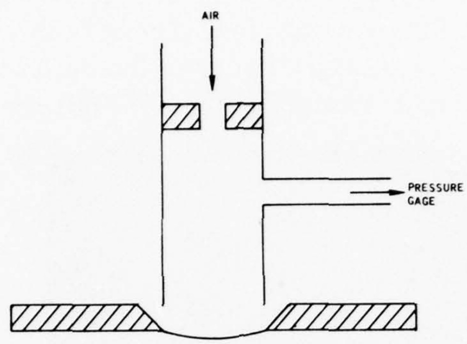


FIG. 6a. Schematic diagram of Block tonometer.

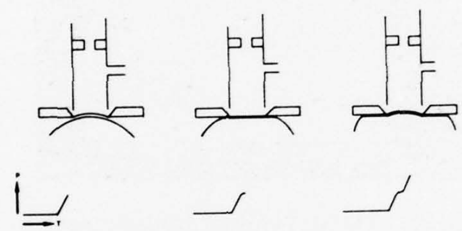


FIG. 6b. Relation between degree of contact of Block tonometer probe with cornea and recorded pressure.

or dip, in the gas back-pressure is recorded (Fig. 6). This tonometer is quite new and is not further considered at this time.

The Schiotz tonometer (Fig. 7) is the typical, indentation tonometer. A handle supports the footplate and plunger so that each

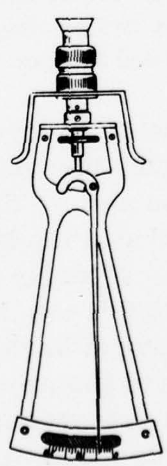


FIG. 7. Schiotz tonometer.

bears on the eye with its own weight. The relative depth of the plunger indentation is associated with the force per unit-area definition of pressure rather indirectly. The plunger forms a somewhat conical indentation. The altitude of the cone is measured, but the base of the cone is the area over which pressure acts to support the weight of the plunger. Recording Schiotz tonometers are available.

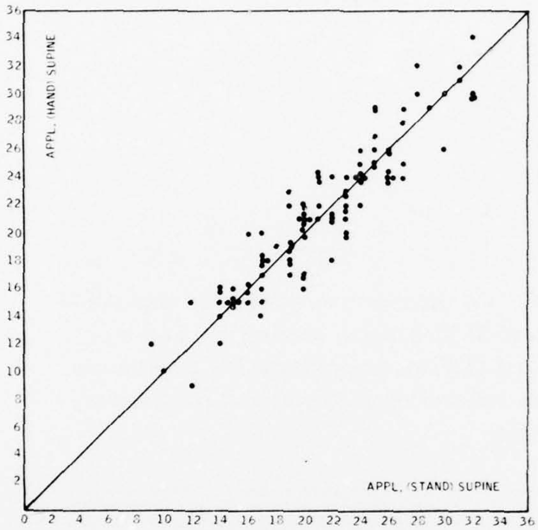


FIG. 8. Comparison of pressure measurement made with two Goldmann applanation tonometers arranged for supine subject. Line is reference slope 1, and not regression line.

If one takes the Goldmann tonometer as a standard, the repeatability of measurement with this tonometer should be a standard for repeatability. Figure 8 shows the results of two successive measurements on a group of subjects with two separate Goldmann tonometers. In this case the tonometers were arranged for the supine patient. The variation between the readings is of the order of ±2.0 mm Hg. Figure 9 is a comparison of Goldmann and Maklakow readings. As expected, the Maklakow tonometer tends to underestimate pressure in an erratic manner. Comparison of the Goldmann and the Schiotz tonometers (Fig. 10) gives more scatter than the repeat Goldmann measurements. Comparison of the Goldmann and the Mackay-Marg with corneal anesthesia (Fig. 11) is not very different from Goldmann versus Schiotz. When no anesthesia is used with the Mackay-Marg the scatter is worse.

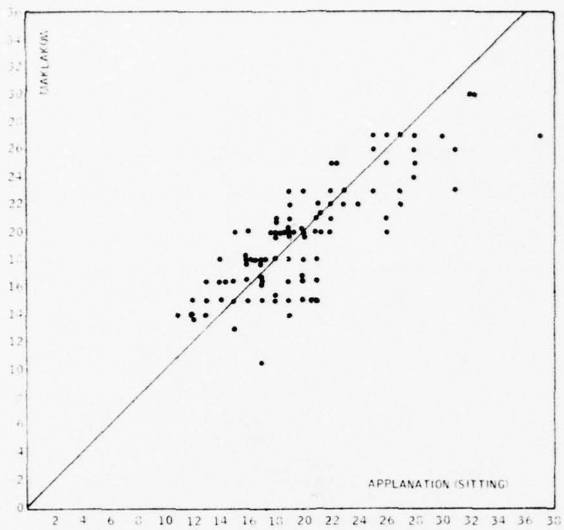


FIG. 9. Comparison of pressure measurements with Maklakow tonometer and with standard Goldmann applanation tonometer. Line is reference slope 1, and not regression line.

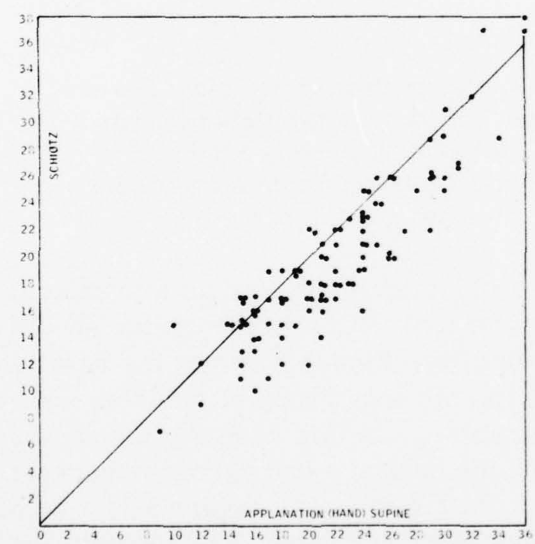


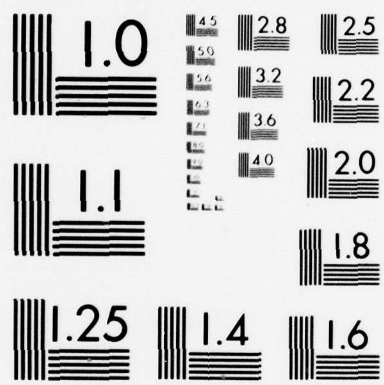
FIG. 10. Comparison of pressure measurements made with Schiotz and Goldmann applanation tonometers (designed for use on supine patient). Line is reference slope 1, and not regresssion line.

AD-A062 145 ARMED FORCES-NRC COMMITTEE ON VISION WASHINGTON D C F/G 6/16
THE MEASUREMENT OF VISUAL FUNCTION PROCEEDINGS OF SPRING SYMPOS--ETC(U)
1968 M A WHITCOMB, W BENSON NONR-2300(05)

UNCLASSIFIED NL

3 OF 3
AD
A062145

END
DATE
FILMED
3-79
DDC



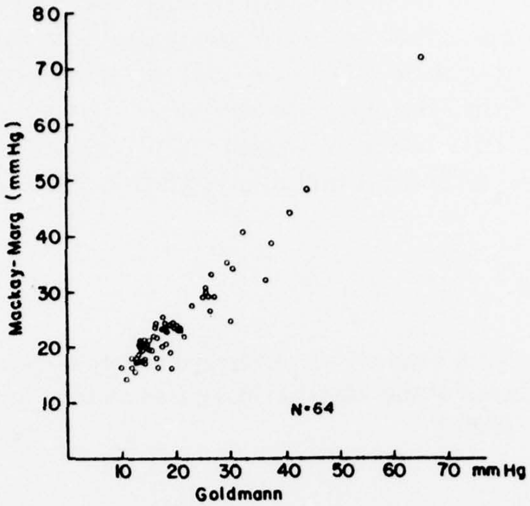


FIG. 11. Comparison of pressures measured by Mackay-Marg and Goldmann applanation tonometers.

For mass screening, the author would eliminate the Maklakow tonometer as too inaccurate, unless methods can be developed to reduce the erratic underestimates of pressure.

Technicians can be taught to use any of these tonometers. The time required for use of each is about the same, although no studies on this point have been reported. If the Goldmann is used in its hand-held form the portability of the instruments is about the same. Both the Schiotz and the Mackay-Marg may be enclosed in sterile, disposable, rubber coverings ensuring against transfer of infection. Only the Mackay-Marg, and possibly the Maklakow, can be used as corneal tonometers without anesthesia.

These considerations would seem to suggest that the Mackay-Marg would be the instrument of choice for screening purposes. However, the only published study comparing the Mackay-Marg with another instrument is the early one by Marg, Oechsli, and the author (Moses, Marg, & Oechsli, 1962). It would seem reasonable that further studies should be conducted before a choice of screening instrument is made.

The grading of intraocular pressure on a scale of ten steps is straightforward. Thus, a simple scale from 0 to 45 mm Hg could be divided in nine equal steps of 5 mm Hg, leaving the tenth step open for very high pressures. There is no insistence on the specific width of the steps.

The emphasis on the measurement of intraocular pressure is questionable. The eye could be more adequately characterized with regard to its hydraulic system if rate of secretion of aqueous, facility of outflow, and episcleral venous pressure were measured as well. Prediction of visual field loss will probably require an estimate of retinal blood-circulation parameters as well.

REFERENCE

Moses, R. A., Marg, E., & Oechsli, R. Evaluation of the basic validity and clinical usefulness of the Mackay-Marg tonometer. Invest. Ophthal., 1962, 1, 1, 78-85. (Feb.)

STRESS TOLERANCE

John Lott Brown, Chairman

EFFECTS OF STRESS ON VISUAL FUNCTION

Introductory Statement by the Chairman of the Section

John Lott Brown
Kansas State University

The concept of stress, although ill-defined, continues to be used widely. In the discussion of the effects of stress on visual function, the concern here is with any readily identifiable agency which disturbs, degrades, or disrupts any aspect of visual function. This section treats both the clinical aspects of stress and the laboratory studies of the effects of stress on various of the visual functions with which this meeting is primarily concerned. Dr. Heinrich Rose, who has had long experience both as a flight surgeon and as an investigator in various agencies of the U.S. defense establishment, has been asked to comment mainly on the clinical aspects. The second paper is primarily concerned with laboratory studies of stress. It is important to point out, however, that the division of this topic by the authors has been somewhat arbitary, and there is a certain amount of overlap in the presentation.

CLINICAL AND FIELD CONSIDERATIONS OF VISION UNDER STRESS

H. W. Rose
Stanford University

Stress in this paper is not restricted to the meaning of the word in Selye's sense. Although some of the stresses discussed will cause effects through that mechanism, a broader meaning of the word is used here. Included are a variety of effects that influence vision, generally in the sense of deterioration of function. However, some functions may be improved under a stress which causes the deterioration of others.

The measurement of visual parameters under stress is not yet common in clinical usage nor in the selection tests for aviation. However, the improved discrimination of visual tests under stress should justify a wider usage. Stresses are discussed that warrant consideration in the clinic, and in the selection of aviators, as well as stresses that are of practical interest in aeronautics and astronautics. There exists a vast literature about the effects of aerospace stresses on man, but due to space limitations, only a few classical studies and some recent work in the field can be quoted.

One can conveniently subdivide stresses into those, that (A) affect the eye indirectly while acting primarily on other organs, and that (B) act directly on the eye.

Hypoxemic Hypoxia (A-1)

Vision is one of the functions most sensitive to the effects of low partial pressure of oxygen in the atmosphere. During ophthalmoscopic examination, both the retinal arteries and veins can be seen to dilate in hypoxia (Dampert, 1929). Cusick et al. found at altitudes of 18,000-21,000 feet (ft) an increase of 10-20 per cent in the diameter of retinal vessels. (Cusick, Benson, &

Boothby, 1940). Duguet et al. saw dilation beginning at 4000 M (about 13,000 ft) and reaching a maximum at 6000 M (about 20,000 ft) within 15 min at altitude (Duguet, Dumont, & Bailliart, 1947). They found an increase in the diameter of the retinal arteries by 10-39 per cent and of the veins by 10-34 per cent. The enlargement of the vessels can also be demonstrated by the enlargment of the blind spot in hypoxia. Ophthalmoscopically, a pronounced change in the colors of the retinal arteries is seen; they become darker and more bluish in hypoxia. The optic disc changes in hypoxia from a light reddish-pink to a bluish gray. Examination with the ophthalmodynamometer shows, as a rule, an increase in the blood pressure of the retinal arteries which goes parallel to the increase in the intracranial arteries.

These reactions of the circulation do not provide a complete compensation for the effects of hypoxemic hypoxia. One finds therefore, a variety of disturbances of visual function in hypoxia. Early balloon and aircraft flights had resulted in reports of improved visual acuity at altitude. These early reports, however, refer largely to experiences that were not properly controlled as to luminance, pupillary diameter, and atmospheric transmission.

McFarland and Halperin (1939-1940) found a decline in visual acuity during hypoxia, especially at low luminances. They report, at a high luminance producing at the retina 1320 "photons"[1] (Troland), and at 18,000 ft equivalent altitude, a visual acuity of 94 per cent of that at ground level. However, with moderately low luminance, producing at the retina 0.144 "photons" (Troland), they report, at 12,000 ft, a decline to 60 per cent of the ground-level visual acuity, and at 18,000 ft, a decline to 45 per cent of the ground-level visual acuity. This decline of visual acuity is even more pronounced at scotopic levels. Visual acuity recovers within seconds with the inhalation of adequate oxygen at altitude. Braun (1950) found in a 7 per cent oxygen atmosphere, corresponding to 7500 M, or 24,000 ft, at luminances of 0.25-0.125 apostilb (asb), or about 0.8-0.4 nit, decreases in visual acuity to 70 per cent of that at ground level.

The size of the pupil has considerable influence on visual acuity and night vision, also, indirectly, on depth perception. For this reason the effect of altitude, especially of hypoxia, on the pupil is of interest. Züst (1940) examined the pupils of twenty subjects in the low-pressure chamber at air pressures

1. "photon" = 1 millilambert $\times$ $10/\pi$ $\times$ area of pupil in mm^2

of 720, 520, and 320 mm Hg, and of three subjects on the Jungfraujoch at air pressure of 520 mm Hg. He used illumination of 0, 15, and 85 lux (lx). In the short experiments in the low pressure chamber, the transition from 720 mm Hg to 520 mm Hg produced a decrease of the pupillary area of 10 per cent in darkness, 14 per cent under 15 lx, and 15 per cent under 85 lx. At an air pressure of 320 mm Hg, the decrease was 15 per cent in darkness, 32 per cent under 15 lx, and 24 per cent under 85 lx. He also found an increased excitability of the light reflex of the pupil. In the longer-term experiment on Jungfraujoch, the pupillary constriction was no longer found, but the light reflexes were still more excitable. Züst considered the constriction and excitability of the pupil an expression of increased parasympathetic tonus in hypoxia. McFarland, Holway, and Hurvich (1942) have confirmed these findings with a different technique, and studied the time course of the pupillary diameter in prolonged hypoxia. For aerospace flight by night, these effects are undesirable; in bright daylight, however, the effect should be considered beneficial.

With sufficiently sensitive tests, a decline of dark adaptation through hypoxia becomes noticeable during fast ascent to altitudes between 1200 and 2000 M (4000 and 6500 ft) in sea-level acclimatized persons. Testing dark adaptation with an Engelking-Hartung adaptometer, Clamann (1938a) at 4000 M (13,100 ft), an increase in threshold by a factor of ten. The difference in monocular and binocular thresholds persisted at altitude, and even increased on breathing oxygen at altitude.

McFarland and Evans (1939) measured at 4600 M (15,000 ft) an increase in threshold after 20 min dark adaptation by a factor of 2.5. Raber (1941) examined the effect of hypoxia on the recovery of mesopic visual acuity after glare. His test had a luminance of 0.16 nit (0.5 asb). After 120 sec at the end of his tests, he found a visual acuity of 0.8 at sea level, 0.7 at 2000 M (6500 ft), 0.55 at 3000 M (10,000 ft), and 0.5 at 5000 M (16,000 ft).

The reported effects of hypoxia on dark adaptation are quite noticeable. They can easily be used to demonstrate to flying personnel the strong effects of hypoxia at altitudes at which the general well-being of the pilot is not yet affected. However, the value of dark adaptation in flying has changed. Scotopic vision has to be re-evaluated in the light of technical advances in flying. A moderate degree of cone adaptation to the mesopic range seems still useful for orientation in present-day flying. Due to the central scotoma and the low resolution, scotopic vision with full rod

adaptation appears of little value for flying with present-day techniques. It is doubtful whether or not, even in World War II, much detection, aiming, and shooting in fighter aircraft was performed with true scotopic vision. Present speeds and weapons systems seem to make the use of scotopic vision in combat largely obsolete. Only a few rather special missions are exceptions to this rule. In the practice of flying, one should, therefore, be concerned with maintaining adequate mesopic adaptation, which, as Raber (1941) showed, is strongly affected by hypoxia.

The influence of hypoxia on color vision was for many years doubtful, due to difficulties in test technique. Reviewing the work of Velhagen (1936), Schmidt (1937a and b), Fichter (1940), and, recently, Okamoto (1962), it seems established that in hypoxia normal trichromates generally remain normal, but equate a wider range of red-green mixtures with yellow on the anomaloscope. Sensitivity for color differences decreases, and the threshold for red is elevated. Red-green retinal rivalry is affected by hypoxia (Rizzo, 1958). Normal trichromates very rarely become color asthenopic. A similar decrease in sensitivity is experienced by color asthenopes and color defectives. The standards of color vision for selection in aerospace flight are poorly validated, and the trend in the practice of flight control is away from color signals in favor of radio communication. There seems to be, at present, a very limited use for color vision in orientation and reconnaissance. Hypoxic effects on color vision, therefore, can at present be considered not critical.

During ascent in the low pressure chamber, Wilmer and Berens (1918) saw a slight enlargement of the visual field at 5000-10,000 ft., but a reduction at 16,000 and 20,000 ft., which concerned mainly the lower part of the field (about 7° for white). Goldmann and Schubert (1933) found nasal and superior restrictions beginning at 4200 M (14,000 ft.), reaching 15° at 6500-7000 M (21,000-23,000 ft.). Kyrieleis _et al._, however, showed that the alleged visual field restrictions were largely due to decreasing attention and that there is no evidence of a true hypoxemic restriction of the peripheral visual field (Kyrieleis, Kyrieleis, & Siegert, 1935). The enlargement of the blind spot can be shown to be real and is concomitant with engorgement of retinal vessels. Recently, Smith and Tully (1965) reported 16-17 per cent loss of visual field at 18,000 ft. in five subjects after 20 mins. They reported a fast recovery: 14.7 per cent of the field was recovered on arrival at ground level, after descending at 5000 fpm to 5000 ft., and then at 500 fpm to ground level.

A full visual field must be considered an essential safety factor in flying under visual control. It does not seem to be critically affected by hypoxia, as long as high levels of luminance are maintained. The combination of hypoxia with low brightness or other stresses may, however, affect the field.

Binocular depth perception with Koch's apparatus was tested on eleven subjects in twelve tests by Heinke (1942) at equivalent altitudes of 5000, 6000, and 7000 M (16,400, 19,700, and 23,000 ft.). He presented each subject with transverse disparities which for him, at sea level, just permitted fusion into a three-dimensional image. Seven subjects showed a decrease, two an increase, and two others wider scatter of the fusion range. Heinke attributes his results to decreasing concentration and a decrease in the efficiency limits of depth perception. Duguet (1947) subjected seven subjects, age 17 to 40 years, to hypoxia in simulated ascents to 6000 M (20,000 ft). Only two of the seven subjects had increases in parallactic angle. The others retained sea-level parallactic angles to 6000 M.

Apparently, depth perception is not affected by mild states of hypoxia. In serious hypoxia near collapse, depth perception is affected but no longer essential. The most critical use of depth perception occurs during refueling and during landing, which generally would not be performed in severe hypoxia.

The range of accommodation seems to deteriorate slightly in hypoxia (by about 1 cm—5 cm at 6000 M or 20,000 ft), but accommodation is a highly subjective test. A determined effort of an ambitious subject easily overrides hypoxic effects during the test. For this reason, the results reported in the literature are contradictory. Nevertheless, there should be some concern with accommodation during longer exposures of unacclimatized subjects to hypoxia.

In an atmosphere of 10 per cent oxygen, as compared to 21 per cent oxygen, Newberry _et al_. report an increase of 61 per cent in the angular velocity of the nystagmus slow phase (Newberry, Johnson, & Smiley, 1965). Hypoxia, thus, increases the disturbances caused by nystagmus.

Hyperoxia (A-2)

For denitrogenation of high altitude and for spacecraft pilots, atmospheres of more than 160 mm Hg partial pressure of oxygen (pO_2) have been used. Cusick _et al_. (1940) saw in 760 mm Hg pO_2 a diminution of retinal arterioles (10.5-37.7 per cent), and of veins (16.2-37 per cent). Twenty-three per cent of the subjects

of Comroe et al. (Comroe, Dripps, Dunke, & Deming, 1945) developed conjunctival irritation after breathing 760 mm Hg oxygen for 24 hours. Morgan et al. report that seven of eight subjects developed eye irritation in an atmosphere of 174 ± 15 mm Hg pO_2 and total pressure of 192 ± 15 mm Hg (Morgan, Ulvidal, Cutter & Welch, 1963). Herlocher et al. exposed four airmen for thirty days to a pO_2 of 254 mm Hg in a total pressure of 264 mm Hg (Herlocher, Quigley, Behar, Shaw, & Welch, 1964). Two of the subjects reported "burning eyes." The night vision of all four subjects was not changed.

Within the limitations of time and the partial pressure required for the protection of the lung, there are apparently no serious effects of high oxygen tensions on the eye.

Carbon Dioxide (A-3)

Wald et al. observed a rise in light thresholds by 0.27 logarithmic units after voluntary hyperventilation which caused hypocapnia (Wald, Harper, Goodman, & Krieger, 1942). Spalter saw a dilation of retinal vessels in hypercapnia (Spalter, Ten Eick, & Nahas, 1964).

Ocular changes from variations in blood pCO_2 seem moderate, and the effects do not appear limiting for tolerance during aerospace flight.

Dysbarism (A-4)

In fast decompression to about 30,000 ft, gas bubbles are formed in tissues and the blood vessels of the body. Ocular symptoms are highly variable, depending on the location of the bubbles; blurring of vision, central scotoma, scintillating scotoma, and diplopia have been seen. The visual field defects are often hemianopic or irregular peripheral restrictions (Flinn & Womack, 1963; Whitten, 1946). Goodman (1964) describes in three cases diplopia, divergent strabismus, random eye movements, and blurring of vision. He treated the symptoms successfully by compression to 2-6 atmospheres absolute, and by oxygen breathing. Fryer (1946) recently described a case of an overweight pilot who suffered, after two hours at only 18,500 ft, what appeared to be decompression sickness with difficulty in focussing, blurred vision, and pupillary disturbances.

Pressure Breathing (A-5)

Green (1961) examined the retina during pressure breathing under 60 mm Hg overpressure and without counter pressure at

the eye. He found slight narrowing of the vessels (5.2 per cent) but no hemorrhages.

Acceleration (A-6)

Although there is no use of acceleration as a stress in clinical examination, acceleration has great interest in actual flight, and is used as a stressor in the evaluation of already trained pilots.

Retinal ischemia due to acceleration forces causes blurring of vision, losses of the peripheral and later central field, and, ultimately, complete blackout. The relative position of the eye to the heart is a major factor in determining blackout levels of acceleration—about 5 (G) in "eyeballs down" acceleration, 11 G in "eyeballs out" acceleration, and about 14 G in "eyeballs in" acceleration (Ruff & Strughold, 1942). Tolerance is lowest for the "eyeballs up" acceleration; at 2-3 G, central scotoma and conjunctival hemorrhages appear (Staff, 1959).

A crouching attitude and pressure on the lower body by an anti-G-suit brought tolerance for "eyeballs down" acceleration to about 6 G, which is sufficient for aviation, even in fast aircraft. For spacecraft re-entry, which produces 10-12 G temporarily, it is customary to position the pilot in an attitude which causes "eyeballs in" acceleration. "Eyeballs out" accelerations have resulted in extensive subjunctival hemorrhages. Scano (1961) reports retinal detachment through acceleration. Hayashi (1965) has caused repositioning of the detached retina by adjusting the direction of acceleration on the centrifuge. Howard (1962) has demonstrated that strong lights can be seen in early phases of the blackout.

Pigg and Kama (1961) have reported 6 per cent reduced visual acuity at 2 G. Frankenhäuser (1938) reports impairment of visual acuity after 2-10 min in 3 G acceleration. Whiteside (1962 b) found, after vertical accelerations, a deviation of the eyes in the upward direction. Visual field defects developed in the subjects of Jaeger *et al.* in a standard pattern: at first nasal restriction, which approaches hemianopsia, then marked temporal field loss (Jaeger, Severs, Weeks, & Duane, 1964). The last remaining field is confined to an island located 5-10° temporal from fixation. Holleman *et al.* evaluated visual field losses from the point of view of the astronaut during launch and injection (Holleman, Armstrong, & Andrews, 1960). In spite of some loss of the peripheral field, control was good to 15 G. There was no serious impairment to 9 G, and by pre-breathing oxygen, control could be maintained during 12-15 G. Steiner (1959) determined the

differences in sensitivity to blackout in red and, after dark adaptation, in white light. He found individual differences ranging from 1.1 G-2.8 G. In the subjects of Beckman et al. volitional ocular motility, optokinetic reflex, and ability to follow a target disappeared with the loss of peripheral vision (Beckman, Duane, & Coburn, 1961; 1962). Schubert and Kolder (1962) found visual clues sufficient to determine the vertical during accelerations up to 2.5 G on the centrifuge. Clark and Graybiel (1962) exposed four men to four hours in a slow rotation room: the subjects experienced no changes in the oculo-gravic illusion. In 20 subjects exposed for three hours to 5, 7.5, and 10 rpm, Lagerwerff observed changes in lateral and vertical phorias, macular stereopsis, divergence and convergence capabilities, as well as peripheral vision (Lagerwerff & Newson, 1964). Whiteside and Campbell (1959) found a size constancy effect during angular and radial acceleration.

Miller and Leverett (1965) determined tolerance to acceleration after four weeks bedrest with loss of central vision as endpoint. Bedrest did not affect tolerance to transverse ($+G_X$) acceleration. It had only insignificant effects on headward ($+G_Z$) acceleration (rapid onset: before bedrest 3.52 G; after bedrest 3.48 G; gradual onset: before bedrest 4.46 G; after bedrest 4.12 G). During vertical turns, loops, dive recovery, Immelmann turns, and cloverleaf patterns, performed in a T-33, Saito and Ishisaki experienced no adverse effects on vision (Saito, Neno, & Ishisaki, 1962).

A greater visual stress is apparently induced during high speed, low altitude flight. In such flights Fraser (1964) measured a buffeting frequency of 2.35 cps, repetitive accelerations of 0.5 G interspersed with 1 G accelerations, and occasionally maximal accelerations of 4 G. His pilots reduced instrument- and map-reading activity to a minimum, and flew mostly in a "heads up" attitude. Wempe (1964), as well as Mercier and Perdriel (1962), attributes degraded performance to fatigue and disturbed vision in low altitude, high speed flight and gusts.

Zero Gravity (A-7)

During short periods of acceleration, Gerathewohl and Stallings (1958) report displacements of visual afterimages in the direction of the acceleration. In short periods of weightlessness ". . .the visual afterimage appeared to rise into the upper part of the apparent visual field. . . . ." Roman et al. observed opposing directions of illusory movements of real objects and afterimages in

accelerations and in 0 G flight (Roman, Warren, Niven, & Graybiel, 1962). Pigg and Kama (1961), during flight in a C 131 B compared visual acuity in 1 G and 0 G, and found a decrement of 6 per cent in 0 G. This was the same decrement found in the transition from 1 G to 2 G. Sasaki (1964; 1965) saw in transient zero G no significant effects on binocular depth perception, but an indication of enhancement during zero G.

White (1965) reports slight, but consistent improvements in brightness discrimination (in 1 G at 0.03 ftL: 15.14 per cent, at 0.28 ftL: 7.05 per cent, at 30.0 ftL: 4.45 per cent; in 0 G at 0.03 ftL: 12.56 per cent, at 0.28 ftL: 6.49 per cent, at 30.0 ftL: 3.99 per cent). However, his one G contrast thresholds must be considered slightly high. Warren et al. could exclude angular accelerations as the principal cause of visual illusions in parabolic flight maneuvers (Warren, Roman, & Graybiel, 1964).

Vibration (A-8)

Subjecting the whole body to vibrations, Coermann (1939) saw maximal deterioration of visual acuity in the frequency bands of 20-40 cps, and 50-90 ops. Visual resolution declined by about 1.2 angular minutes. Loeckle (1950) connected vibrations with autonomic nervous disturbances, which might indirectly influence the eye. Schmitz detected a significant decrement in visual acuity at frequencies of 2.5 and 3.5 cps.

Noise (A-9)

After five minutes exposure to a noise field of 98-105 decibels at frequencies of 50-5000 cps, color recognition was delayed in Grognot and Perdriel's subjects. The visual field for red, and dark adaptation were reduced (Grognot & Perdriel, 1959).

Heat (A-10)

Brandis (1960) exposed dark-adapted subjects to 440 C (111° F). During the first 30 min dark adaptation improved. During the following 60-90 min it deteriorated 13-15 per cent below normal. After a temperature exposure of 55 min to 65.6°C (150°F), subjects of Kissen experienced a facilitation of dark adaptation by heat (Kissen, 1963).

Magnetism (A-11)

By compensating for the normal earth-magnetic field, Beischer et al. exposed men for ten days to fields of only 100 gamma (1 gamma = 10^{-5} Oerstedt). Such low magnetic fields may occur

on the moon. They observed a gradual decrease of the flicker fusion threshold (Beischer, Miller, & Knepton, 1965).

Exercise, Fatigue (A-12)

After exercise of 1 - 1-1/2 hours, Filatov et al. measured a drop of ocular pressure averaging 4.5 mm Hg (Filatov, Iercho-witz, & Fisher, 1937; 1938). Mercier (1962) discusses the many facets of fatigue like exercise, day-night rhythm, climate, emotion, and fatigue by sustained work, all of which can influence vision. Galatioto (1959) considers flicker fusion frequency a sensitive indicator of visual fatigue, caused by turbulence and long flights. Paerisch (1961) saw in recruits no influence on accommodation range by the work week or by prolonged rifle practice. Zagriadskii and Listova (1961) found after fatiguing flight duty a decrease in the number, latency, and duration of afterimages. Heinsius (1941) reports impairment of mesopic and scotopic vision by physical stresses. Graf (1944) could not establish significant differences when he gave five tests each to three subjects before and after a sleepless night. Rose and Schmidt (1947) did not see differences in mesopic and scotopic vision when muscle exercise was performed before or during the tests.

Toxic Substances (A-13)

After an exposure of one to three hours to atmospheres containing 20, 35, and 50 parts per hundred million of ozone, Lagerwerff (1963) established a considerable decrease in scotopic and mesopic visual acuity, but an increase in peripheral vision. During a toxicological evaluation of the aircraft disinfectant, O, Odimethyl-2,2-dichlorovinylphosphate, Rasmussen et al. did not see toxicity for visual functions (distant vision, near vision, accommodation, depth perception, latent phoria near, latent phoria distant, vertical phoria distant, pupil and visual field (Rasmussen, Jensen, Stein, & Hayes, 1963).

Low Luminance (B-1)

Insufficient luminance makes all visual functions difficult. Different functions vary in their sensitivity to low illumination. Visual acuity is quite representative. A visual acuity of 1.7 (20/12) under 300 lx illumination dwindled in König's measurements to 0.15 (20/130) under 0.03 lx illumination (König, 1903). McFarland (1953) had similar results with 293 airline pilots tested, first with 40 ft-c (431 lx) at the chart and 30 ft-c (323

lx) at the eye, and then with 0.05 ft-c (0.54 lx) at the chart and 0.13 ft-c (1.39 lx) at the eye. Their average visual acuity dropped from 20/14 to 20/32. When the pupil opens in low brightness to a diameter of more than 4.5 mm, definition suffers. At 7 mm pupillary diameter, one-third of the visual acuity is lost (Tonner, 1944). These effects can be of practical concern in night flying, in orbit on the night side of the earth, or in shaded areas on the moon.

Glare (B-2)

A detrimental effect can be produced by an excess of light, or by excessive contrast in the visual field; it affects various visual functions. Outside the atmosphere, contrasts are high and solar illumination is about 1/3 higher than at sea-level. In the orbit of Venus, illumination is twice that of the earth orbit. While goggles can reduce the level of apparent luminance, they do not reduce excessive contrast. It is advisable to illuminate deep shadows artificially.

In pilots of World War I, Zade (1916) had described ring-shaped scotomata produced by visible light. These findings were confirmed by Ten Doesschate (1918). But neither Clamann in 1938 nor Rose during World War II could demonstrate such visual field disturbances. It must be assumed that the pilots of the later era were better protected from visual glare. Detailed studies of short-time glare effects on dark adaptation were reported by Kyrieleis (Kyrieleis et al., 1935). Comberg's method was extensively used during World War II to examine the mesopic visual acuity of pilots during simultaneous glare (Comberg, 1941). Significant individual differences were found that could be related to scatter in the media of the eye. Severin et al. reported individual differences in the after-effects on visual acuity of strong glare 86,080 lx, 150,640 lx, and 242,100 lx (Severin, Alder, Newton & Culver). The time of recovery was linearly dependent on illumination. The sun viewed from earth orbit produces an illumination of about 146,000 lx. The luminance in cockpits and the environment at altitudes 5000-20,000 ft. under a variety of weather conditions were measured recently by Pitts and Loper (1963). They found a band 10° above the horizon brightest, and snow and cloud tops about equally bright. Mote et al. reported the effects of pre-exposure to light on visual contrast discrimination (Mote, Biersdorf, Kent & Myers, 1954). Under simultaneous glare or during the after-effects of a glaring light source brighter displays overcome the blinding effect. Hill and Chisum

(1964) give data for necessary display luminances. Fry and Alpern (1952) report the effects of simultaneous glare. Local adaptation plays a considerable role even at blinding luminances. Iarbus (1960) reports that if a test field is kept motionless with respect to the retina, after 2-3 sec., differences within the field cease to be perceived, even when separate parts of the field attain blinding luminances.

Red Light (B-3)

For the protection or rod adaptation, red cockpit illumination is commonly used (see, however, the discussion in A-1 about its usefulness). Reading maps and charts, as well as instrument-reading requires added accommodation (Diamond, 1963). This is due to the chromatic aberration of the eye. More serious are difficulties in map and chart-reading that are caused by the changes in contrast as well as in color, due to the altered spectral composition of the reflected light (Chapanis, 1953). Map and chart features, represented in red pigments, are no longer visible. Many other pigments change apparent contrast and apparent color.

Flicker (B-4)

The effects of intermittent light were studied by Strughold, Autrum, Kornmüller, and Noell for application in flight during World War II. Strughold (1950) found under 200 lx illumination, the frequencies from 3-5 cps especially unpleasant. Flicker light of these frequencies can cause vertigo, discomfort, and drowsiness. Such frequencies occur when pilots look through propellers at idling speeds and through helicopter blades in flight. Johnson (1963) reported flicker in helicopter flight as a problem for one-fourth of 102 pilots. While flicker was generally only annoying, it nearly caused one pilot to have an accident. Recently, Aitken et al. found 1.33 cps scarcely disturbing.

Ganzfeld (B-5)

This is literally the "whole field," a catch-all expression including night myopia (Otero & Duran, 1941), night presbyopia, and empty field myopia (Whiteside, 1962a) or space myopia. The inability to focus in an unstructured field or in a dark field leads in sufficiently young persons to accommodative effort and consequent myopia. The amount depends on age. In night myopia due to spheric aberration and chromatic aberration, combined with Purkinje shift, additional myopia is produced. Ten Doesschate

(1961-1962) saw ganzfeld effects under 1.2 lx and 500 lx, and in fields as small as 20°. Iarbus (1958) saw a decline of motion perception and color vision in the empty field. Held and White (1959) confirmed the underestimation of motion. Miller (Miller & Ludvigh, 1961) emphasized the difficulty of location and the easy disappearance of a once-located object. Mercier (1962) found a lesser susceptibility of myopes to hyperaccommodation. In the refractive measurements of Heath (1962) ganzfeld myopia tended to increase during the first 3-5 minutes. Thereafter, accommodation fluctuated rapidly-about 0.75 diopter (D), occasionally up to 1.5 D. Pomeranz (1963) suggests selection for hyperopia of 0.75 D in pilots on account of ganzfeld effects. However, this could reasonably be applied only to young applicants, and they easily accommodate about 2.5-3 D in the ganzfeld.

Aircraft and Satellite Visibility (B-6)

The problems of seeing small, fast-moving objects under the special conditions of illumination in earth orbit have been examined by Schmidt (1958) and by Rose (1969). Spacecraft and small natural objects in space have the combination of small subtended angle, luminance, and velocity that make them visible only as point source of light up to the time when they may be too close for evasive action. A very similar problem has been presented by atmospheric flight of fast aircraft. Even large transports at super sonic speeds cannot always be seen in time (Fichtbauer, 1963). Diamond (1959) has discussed the lack of time for stereoscopic vision when fast aircraft are on a collision course.

Moving Visual Target (B-7)

The deterioration of visual acuity by a moving target has been studied extensively by Miller and Ludvigh (1961), Goodson and Miller (1959), and Rose (1969) and is well represented in reports to this committee. Jones (1965) has recently demonstrated the failure of the compensatory movements of the eye during aircraft rotational maneuvers.

Visual Fatigue (B-8)

A fatiguing effect on the visual functions by prolonged execution of one task or by other previously performed visual tasks has been demonstrated. Mercier et al. (Mercier, Perdriel, & Ganas, 1959) have discussed the fatiguing effect of the fast moving multitude of visual objects passing through the field in low, fast flight. Zubow (1958) proved visual fatigue after close visual work.

Collins and Pruen (1962) demonstrated fatigue of accommodation after two hours of setting a vernier gauge. Haider and Dixon (1961) found fatigue effects within 2-10 minutes of performance of a differential threshold task. Masci (1962) saw visual fatigue in one hour of tachistoscopic observation. This form of presentation is approached in low, fast flight. Berest (Berest, Perdriel, & Colin, 1958), Fleming, and Soussen et al. (Soussen, Perdriel, & Leblanc, 1962) found fatigue in radar observation.

Summary

A wide variety of aerospace stresses has been described which act directly or indirectly on visual functions. Some, e.g., hypoxia, dysbarism, glare, fatigue, produce significant visual deterioration with serious consequences for aerospace flight. Strenuous efforts for improvement in procedure and in flight technology are warranted for this reason.

The possibility of refining the diagnostic value of visual tests in selection and evaluation of pilots should make desirable a wider use of visual tests under stress (low brightness, glare, hypoxia).

REFERENCES

Aitken, R. C. B., Ferres, H. M., & Gedye, J. L. A subjective assessment of flashing lights. Flying Personnel Res. Comm. Rep., 1962, No. 1194.

Beckman, E. L., Duane, T., & Coburn, K. R. Limitation of ocular motility in humans due to positive acceleration. NADC Johnsville, Pa.: Aviat. med. Accel. Lab. Rep., 1961, No. NADC-MA-6140.

Beckman, E. L., Duane, T. D., & Coburn, K. R. Limitation of ocular motility and pupillary dilation in humans during positive acceleration. In A. Mercier, Ed. Visual problems in aviation medicine. Oxford: Pergamon Press, 1962. Pp. 17-25.

Beischer, D. E., Miller, E. F., & Knepton, J. C. Exposure of man to low intensity magnetic fields. Paper read at ASMA, New York, April. 1965. Aerospace Med., 1965, 36, 137. (Abstract)

Berest, N., Perdriel, G. & Colin, J. Etude statistique de la fatigue visuelle des lecteurs de scope radar. Médecine aeronautique, Paris. 1958, 13, 135-140.

Brandis, S. A. The influence of bromine and caffein on the light sensitivity of the eye and heat regulation in high environmental temperature. Fiziologicheskii Zhurnal SSSR, 1960, 46, 489-494. (In Russian)

Braun, R. Adaptations- und Auflösungsvermögen der Netzhaut im Sauerstoffmangel. Luftfahrtmed., 1945, 9. In H. W. Rose & I. Schmidt. German aviation medicine World War II. 1950, 2, 894.

Chapanis, A.. An evaluation of problems of chart reading under red illumination. AF-NRC Vision Comm. Rep., 1953.

Clamann, H. G. Die Dunkeladaptationskurve des Auges bei Sauerstoffmangel. Luftfahrtmed., 1938, 2, 223-225. (a)

Clamann, H. G. Über Netzhautschadigungen bei Fliegern. Luftfahrtmed., 1938, 2, 314. (b)

Clark, B., & Graybiel, A. Visual perception of the horizontal during prolonged exposure to radial acceleration on a centrifuge. J. exp. Psychol., 1962, 63, 294-301.

Coermann, R. Untersuchungen über die Einwirkungen von Schwingungen auf den menschlichen Organismus. Luftfahrtmed., 1939, 4, 73-117.

Collins, J. B., & Pruen, B. Perception time and visual fatigue. Ergonomics, 1962, 5, 533-538.

Comberg, W. Bemerkungen über Blendungsstörungen des Autofahrers. Klin. Monatsbl. f. Augenheilk., 1941, 106, 480.

Comroe, J. H., Dripps, R. D., Dumke P. R., & Deming, M. Oxygen toxicity. J. AMA, 1945, 128, 710-717.

Cusick, P. L., Benson, O. O., & Boothby, W. M. Effect of anoxia and high concentration of oxygen on the retinal vessel. Rochester, Minn.: Proc. Staff Mtg. Mayo Clin., 1940, 15, 500-502.

Dampert. In C. Monge: Les érythrémies de l'altitude. Paris: Masson, 1929. P. 134.

Diamond, S. Time, space, and stereoscopic vision. Aerospace Med., 1959, 30, 650-663.

Diamond, S. Effects of red lighting on accommodation in aircrew personnel. Aerospace Med., 1963, 34, 1005-1006.

Duguet, J. Le comportement de la parallaxe stéréoscopique en anoxie. La Méd. Aéronaut., 1947, 2, 36-42.

Duguet, J., Dumont P., & Bailliart, J. P. Action de l'anoxémie et de l'inhalation d'oxygène sur la circulation rétinienne. Méd. Aéronaut., 1947, 2, 201-211.

Fenning, L. M. Visual hygiene for radar observers. Opt. J. & Rev. Optom., 1960, 97, 35-36.

Fichtbauer, S. Wahrnehmungsprobleme des Hochgeschwindigkeitsfluges. Deutsche vers. Anstalt. f. Luft-u. Raumf. Med. Rep., 1963, 205, 122-133.

Fichter, H. Über das Verhalten der normalen and anomalen Trichromasie bei Hypoxämie. Doctoral dissertation, Univer. of Freiburg, 1940.

Filatov, V. P., Ierchowitz, I. G., & Fisher, D. G. Die Wirkung einiger Sportübungen auf den Augendruck. Vestn. oftalm., 1937, 11, 154-160. Also Zbl. Ges. Ophthalm., 1938, 40, 574. (Abstract)

Flinn, D. E., & Womack, G. J. Neurological manifestations of dysbarism. Aerospace Med., 1963, 34, 956-962.

Frankenhäuser, M. Effects of prolonged gravitational stress on performance. Acta Psychol., 1938, 14, 92-108.

Fraser, T. M. Aspects of the human response to high speed low level flight. Aerospace Med., 1964, 35, 365-370.

Fry, G. A., & Alpern, M. The effect of a peripheral glare source upon apparent brightness of an object. Amer. J. Optom., 1953, 43, 189.

Fryer, D. I. Decompression sickness at 18,500 ft. Aerosp. Med., 1964, 35, 479-481.

Galatioto. La Frequenza critica di fusione come test di fatica operazionale negli equipaggi del soccorso aereo. Riv. di Med. Aeronaut. e Spaciale, 1959, 22, 148-162.

Gerathewohl, S. J., & Stallings, H. D. Experiments during weightlessness. USAF Sch. of Aviat. Med. Rep., 1958, No. 58-105.

Goldmann, H., & Schubert, G. Untersuchungen über das Gesichtsfeld bei herabgesetztem Sauerstoffdruck der Atemluft. Arch. f. Augenheilk., 1933, 107, 216.

Goodman, M. W. Decompression sickness treated with compression to 2-6 atm. abs. Aerosp. Med., 1964, 35, 1204-1212.

Goodson, J. E., & Miller, J. W. Dynamic visual acuity in an applied setting. Aerosp. Med., 1959, 30, 755-763.

Graf, O. Untersuchungen über die Leistungsschwankungen bei Anwendung verschiedener Nachtsehprüfgeräte. Unpubl. Rep., 1944.

Green, I. D. Response of the human retinal vessels to positive pressure breathing. Aerosp. Med., 1961, 32, 407-411.

Grognot, P., & Perdriel, G. Influence du bruit sur certaines fonctions visuelles. Médec. Aéronaut., 1959, 14, 25-30.

Haider, M., & Dixon, N. F. Influence of training and fatigue on the continuous recording of a visual differential threshold. Brit. J. Psychol., 1961, 52, 227-237.

Hayashi, D. Further model studies of the migratory behavior of detached retinas. Paper read at Assoc. f. Res. in Ophth., Tahoe City, 1965.

Heath, G. G. The time course of night and space myopia. AMRL Rep., 1962, No. TDR 62-80.

Heinke, E. Das Raumsehvermögen im Unterdruck. Luftf. Med., 1942, 6, 174.

Heinsius, E. Untersuchungen über Dämmerungssehleistungen. Klin. Monatsbl. f. Augenheilk., 1941, 106, 443.

Held, R., & White, B. Sensory deprivation and visual speed. Science, 1959, 130, 860-861.

Herlocher, J. E., Quigley, D. G., Behar, V. S., Shaw, E. G., & Welch, B. E. Physiologic response to increased oxygen partial pressure. Aerosp. Med., 1964, 35, 613-618.

Hill, J. H., & Chisum, G. T. Flash blindness: a problem of adaptation. Aerosp. Med., 1964, 35, 871-879.

Holleman, E. C., Armstrong, N. A., & Andrews, W. H. Utilization of the pilot in launch and injection of multistage orbital vehicle. NASA, Edwards, Calif.: Inst. aeron. Sci., Rep. 1960, No. 60-16.

Howard, P. The origin of blackout. In A. Mercier, Ed., Visual problems of aviation medicine. Oxford: Pergamon Press, 1962. Pp. 71-77.

Iarbus, A. L. The perception of images moving across the retina at a fixed speed. Biofizika, 1958, 4, 320-328. (In Russian)

Iarbus, A. L. Perception of images of great brightness, motionless with respect to the retina of the eye. Biofizika, 1960, 5, 293-294. (In Russian) Biophysics. Oxford: Pergamon Press, 1960, 5, 338-340. (Engl. transl.)

Jaeger, E. A., Severs, R. J., Weeks, S. D., & Duane, T. D. Visual field changes during positive acceleration. Aerosp. Med., 1964, 35, 969-972.

Johnson, L. C. Flicker as a helicopter pilot problem. Aerosp. Med., 1963, 34, 306-310.

Jones, C. M. Optokinetic and vestibular influences upon the control of compensatory eye movement during head rotation in various planes. Paper read at ASMA, New York. April, 1965. Aerosp. Med., 1965, 36, 150. (Abstract)

Kissen, A. T. Effect of hyperthermia on peripheral dark adaption rates. J. appl. Physiol., 1963, 18, 600-602.

König, A. Gesammelte Abhandlungen zur physiologischen Optik. Leipzig: J. A. Barth, 1903.

Kühl, A., & Teucher, R. Zur Verbesserung der Nachtsicht aus Flugzeugen mit Ferngläsern. Zentr. f. Wissensch. Berichtswesen, Rep. 1943, No. 1735-1; 1944, No. 1735-2.

Kyrieleis, W., Kyrieleis, A., & Siegert, P. Untersuchungen über das Gesichtsfeld bei Sauerstoffmangel und bei Unterdruck. Arch. f. Augenheilk., 1935, 109, 178.

Lagerwerff, J. M. Prolonged ozone inhalation and its effects on visual parameters. Aerosp. Med., 1963, 34, 479-485.

Lagerwerff, J. M., & Newsom, B. D. Visual changes observed in the manned revolving space station simulator at high rotational speeds. Paper read at Aerosp. Med. Ass. May, 1964. Aerosp. Med., 1964, 35, 273. (Abstract)

Loeckle, W. E. The physiologic effects of mechanical vibration. In H. W. Rose & I. Schmidt, "German Aviation Medicine World War II", Vol. II. Washington: U.S. Govern. Print. Off., 1950. (Chap. VII-C)

Masci, E. Influenza della caffeina sulla "performance" dinamica visiva rilevata mediante campimetria tachistoscopica. Atti della Fondaz. Gio. Ronchi, (Firenze), 1962, 17, 340-346.

McFarland, R. A., Chapman, W. P., Burger, F. D., & Graybiel, A. A study of 300 airline pilots in the early stages of their training. In R. A. McFarland, Human factors in air transportation. New York: McGraw Hill, 1953.

McFarland, R. A., & Evans, J. N. Alterations in dark adaptation under reduced oxygen tension. Amer. J. Physiol., 1939, 127, 37-50.

McFarland, R. A., & Halperin, M. H. The relation between foveal visual acuity and illumination under reduced oxygen tension. J. gen. Physiol., 1939-40, 23, 613-630.

McFarland, R. A., Holway, A. H., & Hurvich, L. M. Studies of visual fatigue. Boston: Harvard Univer., 1942.

Mc Laughlin, S. C., Jr. Summary of the evidence regarding space myopia. Minutes Proc., AF-NRC Vision Comm., Toronto. (Nov.) 1954. (35th Mtg.)

Mercier, A. La myopie spatiale. Rev. de Méd. Aéronaut., 1962, 1, 65-68.

Mercier, A., & Lafontaine, E. La fatigue visuelle des equipages de l'aviation commerciale. Presse Médic., 1962, 70, 2025-2026.

Mercier, A., Perdriel, G., & Ganas, P. La vision dans le vol à basse altitude et a grande vitesse. Médec. Aéronaut., 1959, 14, 15-24.

Mercier, A., & Perdriel, G. Les problèmes visuels dans le vol à basse altitude. In A. Mercier (Ed.), Visual problems in aviation medicine. Oxford: Pergamon Press 1962. Pp. 78-83.

Miller, J. W. The empty visual field in the lab and in the air. Naval Res. Rev. (Wash. D. C.), 1960, 1-6.

Miller, J. W., & Hall, R. J. The problem of motion perception and orientation in the ganzfeld. In M. A. Whitcomb (Ed.), Visual problems of the Armed Forces. Washington: Nat. Acad. Sci. - Nat. Res. 1962.

Miller, J. W., & Ludvigh, E. The perception of movement persistence in the ganzfeld. J. opt. Soc. Amer., 1961, 51, 57-60.

Miller, P. B., & Leverette, S. D. Tolerance to transverse ($+G_x$) and headward ($+G_z$) acceleration after prolonged bedrest. Aerosp. Med., 1965, 36, 13-15.

Morgan, T. W., Ulvedal, F., Cutler, R. G., & Welch, B. E. Effects on man of prolonged exposure to oxygen at a total pressure of 190 mm Hg. Aerosp. Med., 1963, 34, 589-592.

Mote, F. A., Biersdorf, W. R., Kent, G. W., & Myers, J. Visual contrast discrimination as a function of pre-exposure to light. WAFB: WADC Rep., 1954, No. TR 54-80.

Newberry, P. D., Johnson, W. H., & Smiley, J. R. The effect of hypoxia on nystagmus induced by angular acceleration. Paper read at ASMA. April, 1965. Aerosp. Med., 1965, 36, 157. (Abstract)

Okamoto, E., Ikenone, H., & Fujihara, H. Statistical observations of the self awareness during hypoxia. Boei Eisei, Natl. Defense med. J., 1962, 9, 101-102.

Otero, J. M., & Duran, A. Rendimiento fotometrico de sistemas opticos a bajas luminosidades. Anal. de Fisica y Quim., 1941, 37, 459.

Otero, J. M., & Duran, A. Continuacion del estudio de la miopia nocturna. Anal. de Fisica y Quim., 1942, 38, 236.

Paerisch, M. Konstanz der Akkomodationsbreite unter zwei verschiedenen belastungsbedingungen. Acta Biol. et Med. German., 1961, 420-427.

Pigg, L. D., & Kama, W. N. The effect of transient weightlessness on visual acuity, WAFB: WADC tech. Rep., 1961, No. 61-184.

Pitts, D. G., & Loper, L. R., Ambient and cockpit luminance measurements. Aerosp. Med., 1963, 34, 145-149.

Pomeranz, R. B. Hyperopia, exophoria and space. Rev. of Optom., 1963, 100, 29-31.

Raber, F. Uber den Einfluss des Sauerstoffmangels auf das Dunkelsehen. Lilienthal Gesellsch., 1941, Rep. No. 146.

Rasmussen, W. A., Jensen, J. A., Stein, W. J., & Hayes, W. J. Toxicological studies of DDVP for disinfection of aircraft. Aerosp. Med., 1963, 34, 593-600.

Rizzo, P. Sul comportamento della rivalita retinica in condizioni di ipossia e sotto l'azione di alcuni farmaci. Riv. di Medic. Aeron., 1958, 21, 736-743.

Roman, J. A., Warren, B. H., Niven, J. I., & Graybiel, A. Some observations on the behavior of a visual target and a visula afterimage during parabolic flight maneuvers.: SAM Rep. 1962, No. TDR-62-66.

Rose, H. W. Perception and reaction times. In Benson & H. Strughold (Eds.), Physics and Medicine of the atmosphere and space. New York: Wiley, 1969.

Rose, H. W., & Schmidt, I. Beeinflussung der Dunkeladaptation. Klin. Wochenschr., 1947, 24, 278.

Ruff, S., & Strughold, H. Atlas der Luftfahrtmedizin. Leipzig: Barth, 1942.

Saito, I., Ueno, Y. & Ishisaki, M. G-load during special flight in the T-33. Boei Eisei, Natl. Def. Med. J., 1962, 9, 99-100.

Sasaki, E. H. Zero gravity - the effect of transient weightlessness on binocular depth perception. Paper read at Aerosp. Med. Assoc., Miami, May, 1964. Aerosp. Med., 1964, 35, 279. (Abstract)

Sasaki, E. Effect of transient weightlessness on binocular depth perception. Aerosp. Med., 1965, 36, 343-344.

Scano, A. Manifestazioni patologiche oculari causate ed aggravate del volo. II World & IV Europ. Congr. on Aviat. & Space Med., 1961, 1, 208-227.

Schmidt, I. Farbensinnuntersuchungen an normalen und anomalen Trichromaten im Unterdruck. Luftf. Med., 1937, 2, 55-71. (a)

Schmidt, I. Farbensehen im Unterdruck. Luftf. Med., 1937, 2, 230. (b)

Schmidt, I. Farbensehen and Hohenwirkuing. Klin. Wochenschr., 1939, 1, 139.

Schmidt, I. Spaces of potential visibility of artificial satellites for the unaided eye. Proc. VIII Intern. Astr. Congr., (Barcelona, 1957). Vienna: Springer Verlag, 1958.

Schmitz, M. A. The effect of low frequency high amplitude whole body vertical vibration on human performance. Milwaukee, (Wisc.): Bostrom Res. Labs., Rep., No. 128 AD-218 201.

Schubert, G., & Kolder, H. Factor analysis of space orientation. Riv. de Medic. Aeronaut. e Spaz., 1962, 25, 64-86.

Severin, S. L., Newton, N. L., & Culver, J. P. A new approach to the study of flash blindness. Arch. Ophth., 1962, 67, 578-582.

Severin, S. L., Alder, A. V., Newton, N. L., & Culver, J. F. Photostress and flash blindness in aerospace operations. Aerosp. Med., 1963, 34, 1095-1098.

Smith, W. L., & Tully, J. J. Peripheral visual field loss at altitude and recovery rates with descent. (Paper read at ASMA, April, 1965) 1965, Aerosp. Med., 36, 163. (Abstract)

Soussen, G., Perdriel, G., & Leblanc, M. Etude préliminaire sur la fatigue oculaire chez les lecteurs de scope-radar par le détermination de la frequence critique objective de fusion du scintillement. Rev. de Médec. Aéronaut., 1962, 1, 52-53.

Spalter, H. F., Ten Eick, R. E., & Nahas, G. G. Effect of hypercapnia on retinal vessel size at constant intracranial pressure. Amer. J. Ophth., 1964, 57, 741-745.

Stapp, J. P. Human tolerance to accelerations of space flight. p. 464 In Benson & H. Strughold, (Eds.), Physics and medicine of the atmosphere and space. New York: Wiley, 1959.

Steiner, S. H. Standardization of an endpoint to positive acceleration on the human centrifuge. WAFB: WADC tech. Note, 1959, No. 59-426.

Strughold, H. Intermittent light. In H. W. Rose & I. Schmidt, German aviation medicine World War II, Vol. II. Washington; U.S. Govern. Printing Office: 1950. (Chap. IX-H)

Ten Doesschate, G. *Über Gesichtsfeldstörungen bei Fliegeroffizieren.* Zeitschr. f. Augenheilk., 1918, 39, 30.

Ten Doesschate, G. Vision in an empty visual field. Aeromedica acta, 1961-62. 8, 91-101.

Tonner, F. Die Sehschärfe. Pflügers Archiv., 1944, 247, 183.

Velhagen jun., K. Die hpoxämische Farbenastheopie, eine latents Störung des Farbsinnes. Arch. f. Augenheilk., 1936, 109, 605.

Wald, G., Harper, P. V., Goodman, H. C., & Krieger, H. P. Respiratory effects upon visual thresholds. J. gen Physiol., 1942, 25, 891-903.

Warren, B. H., Roman, J. A., & Graybiel, A. Exclusion of angular accelerations as the principal cause of visual illusions. Aerosp. Med., 1964, 35, 228-232.

Wempe, T. E. Effects of gust induced and maneuvering acceleration stress on pilot-vehicle performance. Paper read at Aerosp. Assoc. Miami May, 1964. Aerosp. Med., 1964, 35, 284. (Abstract)

White, W. J. Effects of transient weightlessness on brightness discrimination. Aerosp. Med., 1965, 36, 327-331.

Whiteside, T. C. D. Problems of empty visual fields. In A. Mercier (Ed.), Visual problems in aviation medicine. Oxford: Pergamon Press, 1962. Pp. 118-120. (a)

Whiteside, T. C. D. Small eye movements during vertical acceleration. Rev. de Médec. Aéronaut., 1962, 1, 35-37. (b)

Whiteside, T. C. D., & Campbell, F. W. Size constancy effect during angular and radial acceleration. Quart. J. exp. Psych., 1959, 11, 249.

Whitten, R. H. Scotoma as a complication of decompression sickness. Arch. Ophth., 1946, 36, 220.

Wilmer, W. H., & Berens, C. The effect of altitude on ocular functions. J. AMA, 1918, 71, 1394-1398.

Wulfeck, W., Weisz, & Reb, M. W. Vision in military aviation. WAFB: WADC tech. Rep., 1958, No. 58-399.

Zade, M. Über Blendung im Fliegerdienst. Klin. Monatsbl. f. Augenheilk., 1916, 57, 152.

Zagriadskil, V. P., & Listova, N. M. Afterimages in flight activity. Voenno meditzinskii zhurnal. 1961, 61-64. (In Russian) Milit. med. J., 1961, 83-87. (Engl. transl.)

Zubow, V. F. The measurement of visual fatigue. Voenno meditzinskii zhurnal, 1958. 53-55. In (Russian) Milit. med. J., 1958. 19:79-81. (Engl. transl.)

Züst, E. Das Verhalten der Pupille bein Abnahme des Luftdrucks. Luftf. Med., 1940, 4, 209.

SUPPLEMENTAL REFERENCES (Extensive references to earlier pertinent work)

McFarland, R. Human factors in air transportation. New York: McGraw-Hill, 1953.

Mercier, A. (Ed.) Visual problems in aviation medicine. Oxford: Pergamon Press, 1962.

Mercier, A., & Duguet, J. Physio-pathologie oculaire de l'aviateur. Paper read at Societe d'Ophthalmologie de Paris, November, 1947. (English translation published by USAF School of Aviation Medicine)

Rose, H. W., (Parts IX A, C, E & F) & Schmidt, I. (part IX D). In German aviation medicine, World War II, Vol. II. Washington: US Gov. Printing Office, 1950.

LABORATORY STUDIES OF THE EFFECTS OF STRESS ON VISUAL FUNCTION

John Lott Brown
Kansas State University

The present discussion is primarily concerned with three general classes of stress. These include (a) unusual patterns of motion to which an observer may be subjected; (b) various agents which may be ingested, inhaled, or contacted; and (c) aspects of the visual world itself, such as excessively high light levels. There are a variety of other forms of stress which are extremely important, but these will not be treated in this report. They include various psychological factors, prolonged use of the eyes, and general fatigue. Emotional stresses are of obvious importance, but these have not been treated extensively in the laboratory.

There are a variety of ways of assessing effects of stress on quantitative scales. A scale of individual tolerance may be established in terms of the amount of a stressing agent which is required to produce a criterion sensory effect. An example of this is a procedure which is commonly employed in connection with studies of the effects of accleration. A fixed visual criterion, such as the inability to respond to a flashing light, is employed, and the amount of acceleration required to disrupt the subject's response to the light is determined (Brown, 1961 a; White, 1961). An alternative procedure is sometimes used in the study of hypoxia. A number of subjects may be exposed to a given pressure altitude, or to reduced partial pressure of oxygen, and the effect of exposure in terms of the amount by which a visual threshold is elevated can then be determined as an index of stress (McFarland, Halperin, & Niven, 1944).

The problem of selecting an appropriate sensory effect is a serious one. The conventional criterion of "blackout," which has been widely used in acceleration studies, may not be the

most valid criterion that could be used. There are a variety of visual functions which might be employed: visual acuity, stereopsis, visual fields, luminance discrimination, and others, with variations in such parameters as luminance, adaptation, and wave-length distribution. Ideally, the criterion should be one which has some relation to the practical situations in which aviators may be exposed to stress. It is not always easy to relate a complex operating situation to a single, basic visual function, however. The best laboratory approach, if not ruled out by economic or practical considerations, may be one in which functional relations of a number of the relevant parameters for several basic visual functions are established over a wide range of conditions for all possible variables.

MOTION

Acceleration

Serious effects upon visual function may accompany changes in velocity in both aircraft and rocket vehicles. Acceleration is primarily associated with changes in direction in aircraft, and with changes in linear speed in rocket vehicles. The most dramatic effects on vision are encountered under conditions of positive acceleration. As used here, "positive" refers to the line of action of the accelerating force with respect to the long axis of the body. An acceleration in the headward direction, such that body fluids will tend to move toward the lower extremities, is called positive acceleration by physiologists (Hardy, 1964). It is accompanied by a decrease in venous return from the lower extremities, and an increase in the hydrostatic pressure differential between the region of the eyes and the heart. Normally, intraocular pressure exceeds intracranial pressure by approximately 16 millimeters of mercury (mm Hg). Circulation to the retina may, therefore, be cut off earlier than general cerebral circulation during exposure to positive acceleration. Observations of the retina, which have been made during exposure to acceleration, reveal that retinal ischemia can be observed at about the same time that the visual symptoms of blackout occur (Duane, 1954). Central factors may also be significant in the determination of blackout effects, but it is well documented that visual loss may occur prior to the loss of consciousness (Brown, 1961 b).

Gross effects of acceleration on vision have been studied in

a variety of ways. In the early experiments, subjects were simply required to report their symptoms. They gave introspective accounts of graying of vision and a closing in of the visual field to a small, central region prior to complete loss of vision. A more refined approach to the study of visual effects was introduced by requiring subjects to respond to the presentation of lights, located either in the peripheral or central visual field, by pressing a button immediately when the light was observed to come on. This provided the objective information of whether the observer was able to respond accurately to a light presented at random intervals. It has been suggested that additional quantitative information may be obtained by measuring reaction time of the response to a visual stimulus. The reaction time represents a specific quantitative measure of the time interval between presentation of a visual stimulus and the subject's response. This could conceivably show some continuous relation to the "state of the organism" as influenced by acceleration exposure. Several experiments have been performed to study visual reaction time under various conditions of acceleration exposure (Brown & Burke, 1958). Average reaction time shows a positive correlation with level of acceleration. As acceleration is increased, reaction time to a visual stimulus also shows an increase. This is true for both high luminance and low luminance test lights. The order of magnitude of reaction time is strongly influenced by the luminance level of the test light. Results of an experiment on reaction time are illustrated in Fig. 1. The variation in level of reaction time with luminance is clearly evident, as is a difference in the nature of the function for two subjects. Unfortunately, the variability of visual reaction time in an acceleration experiment is high, and individual measures are of little value in assessing a given subject's condition. Functions, such as those presented in Fig. 1, are obtained only by averaging many responses.

A distinction is frequently made between subjective and objective measures of the response of an experimental subject. In this context, even though reaction time is an objective datum based on a relatively precise measurement of the interval between presentation of a stimulus and the objective fact of a subject's response, this is considered a subjective measure because it depends on the subjective awareness of the subject of the stimulus presentation. An example of an objective measure would be the electroretinogram (ERG). This is a measurement of a physical-physiological process which is induced by the action of the

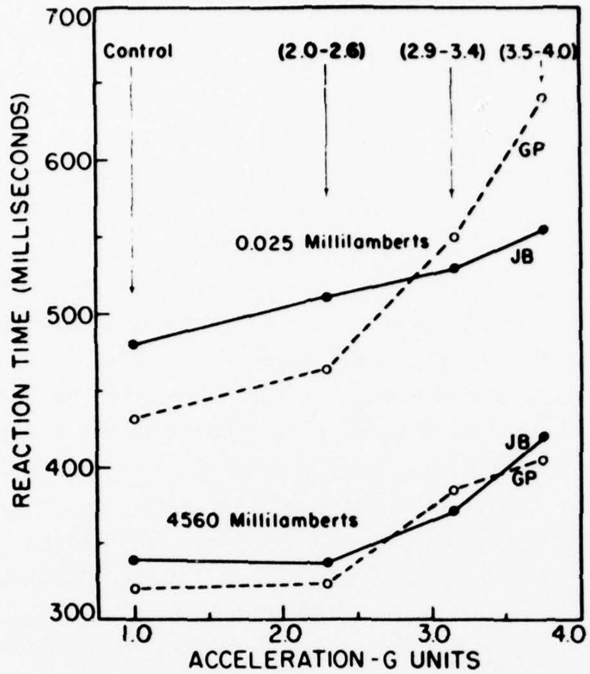


FIG. 1. Average reaction times of each of two subjects during exposure to peak acceleration values as indicated for each of two test light luminances (Brown & Burke, 1958).

stimulus. At least one experiment has been performed in which the electroretinogram was measured during the exposure of subjects to various levels of acceleration on a centrifuge (Lewis & Duane, 1956). Amplitude of the ERG response did not provide a measure which varied in any clear systematic way with the level of acceleration exposure. Data have been presented which indicate that the electroretinogram is relatively insensitive to reduced oxygen (Brown, Hill, & Burke, 1957; Hill, 1960); and, if the visual symptoms which accompany acceleration are actually a manifestation of local ischemia, then the relative insensitivity of the electroretinogram is not surprising. Another measure which has been employed is based on ocular motility (Coburn, Beckman, & Duane, 1963). The eyes of an observer are monitored by closed circuit television during exposure to acceleration. A reduction in eye movement may be observed as the level of acceleration is increased. Observation of spontaneous eye movements and their reduction would constitute a kind of objective measure. On the other hand, if eye movements are made in response to lights illuminated at various regions in the visual

field to which the subject is instructed to direct his gaze, then this type of measure is similar to the reaction time experiment in which the subject presses a key. Loss of motility may represent the direct action of acceleration on eye movement, or may accompany visual loss (cf. Brown & Burke, 1958). Which type of measure is more appropriate can be established only by comparative study.

An interesting series of experiments on visual function as influenced by acceleration has been performed by White and his colleagues (White & Monty, 1963). They have demonstrated an increase in both foveal and parafoveal thresholds during exposure to positive acceleration (Fig. 2). Other acceleration orientations were shown to have a lesser effect on visual thresholds.

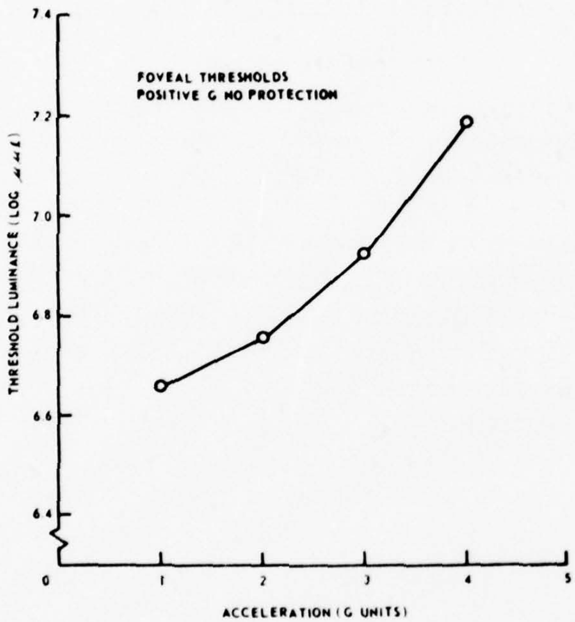


FIG. 2. Foveal luminance thresholds as function of acceleration (White & Monty, 1963).

In studies of visual acuity, impairment of this function was found to be relatively unrelated to the orientation of acceleration (Fig. 3). The investigators concluded that the mechanism of interference with visual thresholds may be reduced retinal circulation, but that the effects on visual acuity are more readily explained in terms of distortions within the ocular media, which are relatively independent of the orientation of the acceleration vector in the scope of their effect. Of practical importance, these investigators have shown that an increase in positive acceleration

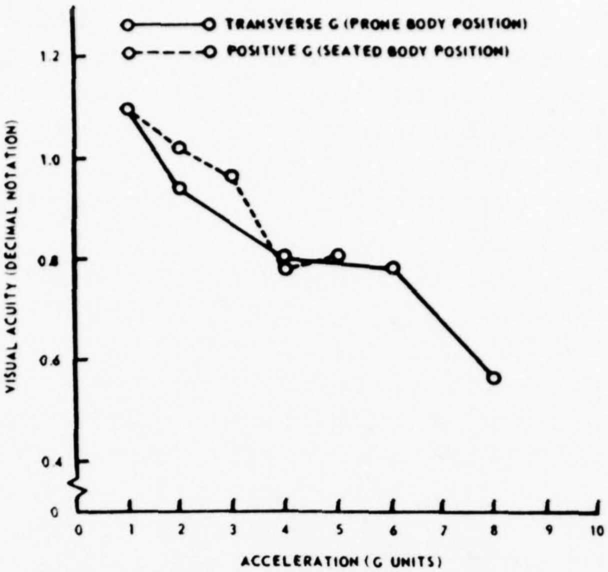


FIG. 3. Binocular visual acuity as function of acceleration for both positive and transverse G exposures (White & Monty, 1963).

may be accompanied by an increase in the number of errors committed in the reading of instrument dials. Performance could be improved by increasing the level of illumination. Exposure to positive acceleration of four (G) could be compensated by an increase in luminance of one log unit.

In a discussion of the subject of acceleration, it is appropriate to consider the effects of weightlessness, or the absence of a gravitational accelerative force, on visual processes. Pigg and Kama (1961) have observed a moderate decrease in visual acuity under zero G. Some negative effects of exposure to zero G on visual function are referred to by Dr. Rose. White (1964) has recently reported a slight improvement in brightness discrimination at zero G.

Vibration

A kind of motion which may have a direct negative effect on vision is vibration (Wulfeck, Weisz, & Reb, 1958 b). Vibration frequencies of approximately 40 cycles per second (cps) are encountered in passing through the sound barrier. The most severe deterioration of visual functions occurs between 12 and 23 cps. There is considerable interindividual variability in the effects of vibration on vision, some of which may be explained

in terms of the fact that vibrations are often measured on the structure supporting the subject, and that the vibration of the eyes varies greatly from one subject to another in accordance with differences in physique (Fig. 4). At somewhat lower frequencies (3 to 8 cps), higher amplitude vibrations may cause severe chest pains which are associated with internal injury.

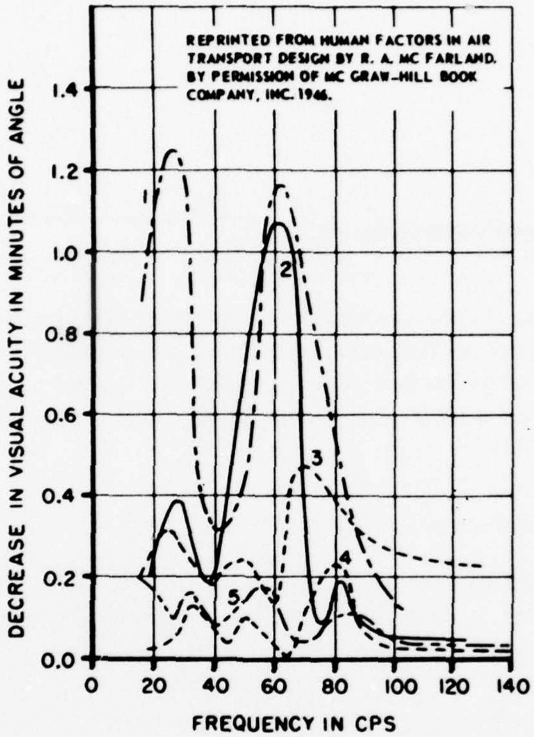


FIG. 4. Decrease in visual acuity (minutes of visual angle) as function of vibration frequency for each of five different subjects (Wulfeck, 1958).

In one study of visual effects (Teare & Parks, 1963), frequencies between 1 and 27 cps were investigated in terms of their effect on the number of errors made in reading counters. Amplitude was adjusted for each frequency in order to maintain subjectively equivalent levels of discomfort, independent of frequency change. Some of the results are illustrated in Fig. 5 for counters having each of five digit heights. These represented visual angles of from 6 to 24 minutes of arc. It is clear that the visual task is markedly influenced only for the two smallest digit sizes, and that the effect is greatest between 12 and 23 cps.

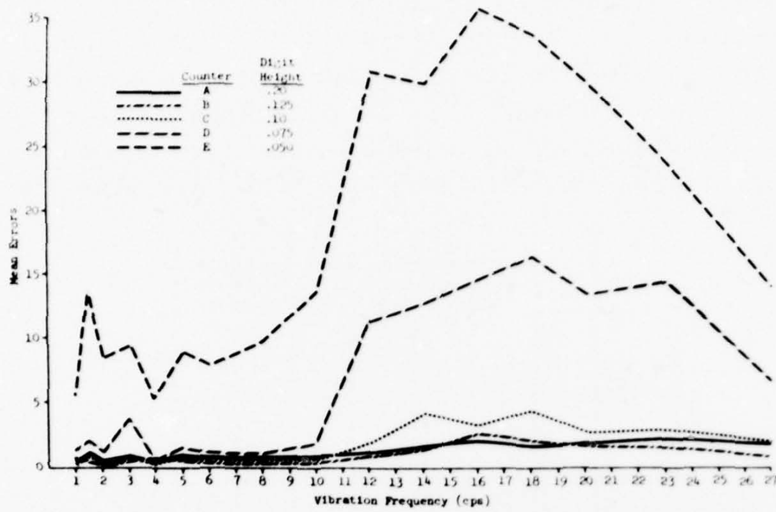


FIG. 5. Mean error of reading as function of vibration frequency for each of five counters with digit heights ranging from 0.05 to 0.20 inches (6 to 24 minutes of arc). Amplitude adjusted to a subjective criterion at each frequency (Teare & Parks, 1963).

Disorienting Rotations

Angular rotations of the pilot of a vehicle which is moving in three dimensional space may result in visual illusions (Clark, 1963). An example of this is provided by rotating a subject on a centrifuge device when he is removed from the center and facing the vertical axis of rotation. If he is in a seated position he will experience an illusion of tilting backward as the angular rate of rotation is increased, and the component of centripetal acceleration builds up. As this occurs, the resultant acceleration vector rotates from the vertical orientation of gravity to the rear, as would the gravitational vector were he actually being tilted to the rear. If a light or other object visible to a subject and in a fixed position relative to him is observed under these conditions, it will appear to move upward at the same time the subject feels himself to be tilting backward. The illusion is a most compelling one. It is clear that visual perception is dependent on more than just vision.

An excellent example of the multisensory dependence of perception is provided by a recent experiment reported by Klein and his associates (Klein, Wapner, Shaw, Cohen, & Werner, 1964). Klein measured the bilateral difference in muscle action poten-

tial in the sternocleidomastoid muscles of subjects tilted laterally away from the vertical. Subjects tilted in this fashion were able to correct the orientation of a luminous rod which tilted with them back to a near vertical position. In a subsequent experiment, differential bilateral tension in the sternocleidomastoid muscles was induced by off-balance weighting of a harness on the head. Under these conditions, when both the subject and the luminous rod were in the vertical position, the rod appeared to be tilted. Subjects were instructed to adjust the rod position so that it appeared vertical. The direction and the amount of the apparent tilt thus measured were comparable to the actual amount of tilt which induced the same differential muscle action potential.

It is clear that variation in the tension of postural muscles, as well as vestibular effects, may influence visual perception. It is probably not possible, under most circumstances, to abstract the influence of any one sensory dimension on one's perception of the environment.

Another visual illusion associated with angular rotation is the impression of continued rotation after actual rotation has ceased. This is called the oculogyral illusion (Graybiel & Hupp, 1946). The appropriate stimulus for this effect is angular acceleration, or deceleration. Thus, when angular rotation is stopped, the impression of continued rotation is induced by the deceleration. This kind of effect may be a serious factor in the false perceptions to which the pilots of vehicles which move in three-dimensional space are subject. Angular rotations in one direction, which are achieved with high acceleration, may give rise to a continuing sense of rotation in that direction, even after return to the original position has been initiated, if the accelerations which accompany reversal of direction are sufficiently low.

The effects of stimulation of the semicircular canals by angular acceleration have been explained in terms of a theory which treates the crista as a damped pendulum, the displacement of which is proportional to the excitation of the mechanism (von Egmond, Groen, & Jongkees, 1949). The adequacy of this kind of theory has been tested in a number of experiments. One of these (Guedry, Peacock, & Cramer, 1957) is illustrated in Fig. 6. A fixed amount of angular acceleration in one direction is introduced. The time required for compensation of the effects of this initial acceleration is then measured for various magnitudes of acceleration in the opposite direction.

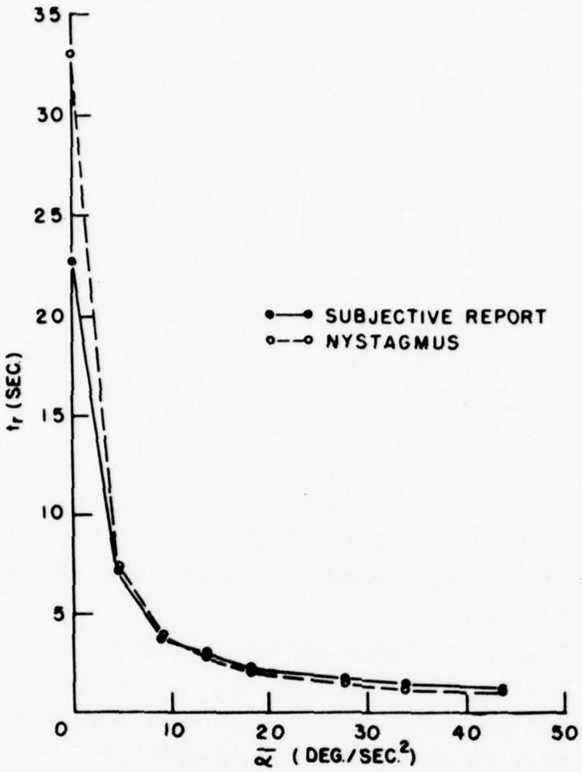


FIG. 6. Interval between commencement of deceleration and termination of subjective reports of apparent rotation or nystagmus, induced by initial acceleration as function of deceleration rate. Data correspond closely to curves derived from "torsion pendulum" theory (Guedry, Peacock, & Cramer, 1957).

VARIATIONS IN THE ATMOSPHERIC ENVIRONMENT

Atmospheric Oxygen

Variations in atmospheric oxygen can produce a variety of effects which influence vision. In 1921, Dautrabande and Haldane (1921) observed that breathing 100 per cent oxygen at sea level pressure is accompanied by a slowing of blood flow, and a constriction of retinal vessels. Effects on visual function in the human of breathing 100 per cent oxygen at sea level have not been observed (Gallagher, Mamman, Nobrega, & Turaids, 1965), but retinal degeneration in rabbits under these circumstances has been reported by Noell (1955). An atmosphere of 100 per cent oxygen at sea level pressure is known to be toxic, and it has been estimated that the limit on duration of exposure for men

without irreversible effects is approximately 70 hours. The reduction in caliber of retinal arteries and veins may be as much as 37 per cent after breathing 100 per cent oxygen at sea level for 30 minutes (Cusick, Benson, & Boothby, 1940).

Effects of hyperbaric oxygen have become of concern recently in connection with the U.S. space flight program. An atmosphere of 100 per cent oxygen is employed in the satellite vehicles at a pressure equivalent to 28,000 feet (ft). Under these conditions, the oxygen pressure is in excess of the partial pressure of oxygen in normal air at sea level. A recent study of visual processes under these conditions for exposures up to 72 hours revealed no deleterious effects on vision (Gallagher et al., 1965). Such functions as flicker fusion frequency, dark adaptation, retinal fields, the electroretinogram, and intraocular pressure were measured.

Reduced Oxygen Pressure

The sensitivity of visual function to reduced oxygen pressure has been recognized for some time. Extensive studies of the effects that reduced oxygen pressure has on vision were conducted during World War II (Berger, McFarland, Halperin, & Niven, 1943; Hecht, Hendley, & Frank, 1943; McFarland et al., 1944; Wald, Harper, Bookman & Kreiger, 1942). When experimental procedures are sufficiently sensitive, reduced visual sensitivity becomes evident at altitudes as low as 5,000 ft. Reduction of sensitivity increases with increased altitude up to the maximum altitude which can be tolerated safely without special adaptation, or increased oxygen concentration. This is approximately 20,000 ft. The results of one experiment (McFarland & Evans, 1939), in which the course of dark adaptation was studied, are presented in Fig. 7. When subjects were breathing in an atmosphere of lower than normal partial pressure of oxygen, the final dark adaptation threshold was higher than normal. Upon administration of 100 per cent oxygen to these subjects, the threshold was further reduced.

Carbon Monoxide Effects

Carbon monoxide has a high affinity for hemoglobin and, therefore, when inspired, tends to reduce the amount of hemoglobin available for binding oxygen and, hence, the effectiveness of oxygen exchange. Visual symptoms may provide the most sensitive indicator of the effects of small amounts of carbon monoxide (McFarland, 1953; McFarland, Roughton, Halperin, & Niven, 1944). A good example of this can be found in the elevation of

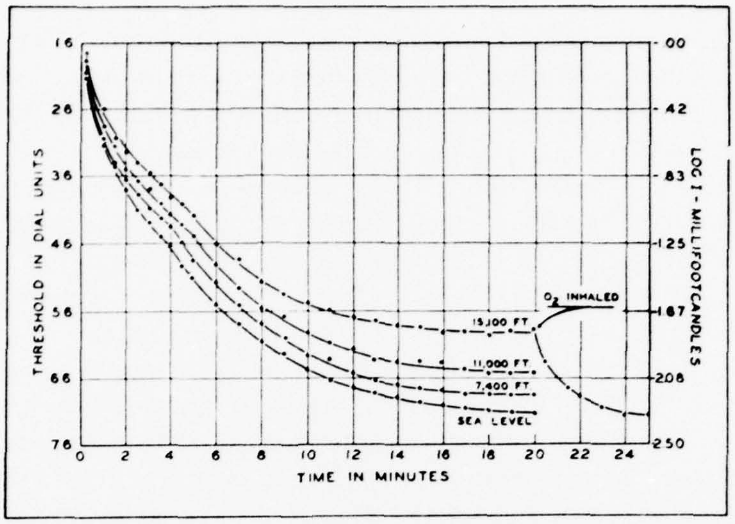


FIG. 7. Visual threshold as function of time in dark for each of three simulated altitudes and sea level. Further threshold reduction upon administration of 100 per cent O_2 is illustrated (McFarland & Evans, 1939).

threshold which results from cigarette smoking. Carbon monoxide inhaled with cigarette smoke is bound by hemoglobin, reducing the efficiency of oxygen utilization. There is an attendant elevation of visual thresholds. The results of an experimental evaluation of this problem are illustrated in Fig. 8. Other effects of cigarette smoking have also been observed. These include a reduction in size of the retinal field. This kind of effect might arise from the vasoconstricting action of nicotine, rather than from the binding of hemoglobin by carbon monoxide.

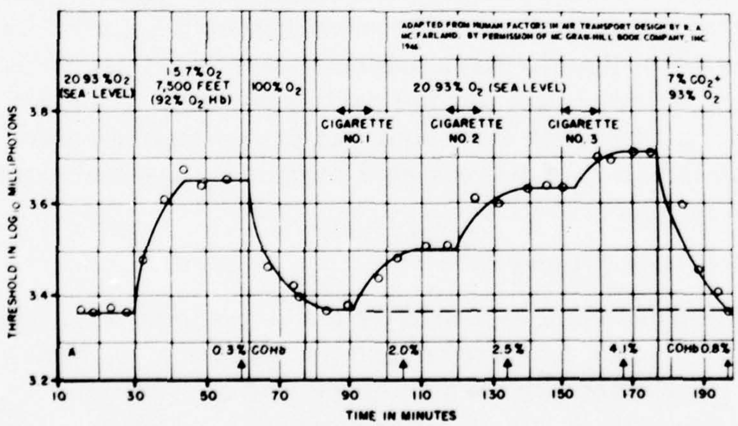


FIG. 8. Effect of cigarette smoking on visual thresholds as compared with effect of altitude (McFarland, 1953).

Atmospheric Contaminants

A variety of agents may be found in the atmosphere provided to aviators and astronauts for breathing. Contaminants found in the oxygen supply of military aviators have occasionally given rise to problems. In space flight, increased atmospheric ionization may give rise to a variety of effects. One possibility is an increase in the concentration of ozone (Lagerwerff, 1963). There is a natural increase in ozone concentration with altitude. Concentration reaches a maximum of 15 parts per million at an altitude of approximately 70,000 ft. Measurements in jet passenger cabins have detected ozone in amounts of from 6.5 to 12 parts per hundred million. Young (Young, Shaw, & Bates, 1962) has calculated that the ozone concentration in a jet passenger compartment may rise to as much as 30 or 40 parts per hundred million. A study of the effects of ozone has been performed by Lagerwerff (1963). Concentration of 20 parts, 35, and 50 per hundred million were studied in exposures of three and six hours duration. An excessive fatigue, or lethargy, was reported by approximately one-third of the subjects. Visual functions such as acuity, stereopsis, vertical phoria, and color vision showed no effects of ozone exposure. There was some indication of change in lateral phoria in 111 out of 145 pairs of pre-exposure and post-exposure measurements by from 1 to 4 1/2 prism diopters. These effects were found in 38 out of 41 subjects. An apparent increase in the peripheral field was found in 25 subjects. Two showed a decrease in peripheral fields. In addition, there were some indications of a deterioration of night vision.

DRUG AND CHEMICAL EFFECTS

One of the effects of ingesting alcohol is a reduction in the effectiveness with which body tissues can utilize the oxygen of the blood. Excessive alcohol may result in a reduction of depth perception, contrast discrimination, and field size. An incoordination of the extraocular musculature may also result. Many of the effects of alcohol on vision may be central rather than peripheral (Alpern, 1962).

A variety of drugs have been found to have an effect on vision (Becker, 1954; Faucett, 1953; Mackworth & Winson, 1947; Rowland, 1942; Wulfeck, Weisz, & Reb, 1958 a). These include the sulfonamides, antihistamines, atabrine, and aspirin. These have been shown in various experiments to interfere with depth per-

ception and acuity, to enlarge the blind spot, and to reduce muscular coordination. A positive effect of chemical ingestion is illustrated by the fact that the ingestion of sugar may offset effects of hypoxia (Simonson, Brozek, & Keys, 1948).

There are a variety of chemicals and drugs which appear to have specific effects on vision. These include acetazolamide, or "Diamox," which is an inhibitor of carbonic anhydrase (Becker, 1954). This drug causes an immediate fall in intraocular pressure, and slows or inhibits bodily secretions in general. This has been used in the treatment of glaucoma. Diamox poisons the active transport mechanisms responsible for the elaboration of fluid. A reduction in pressure may be due to modification in flow resistance.

Dinitrophenol (D.N.P.) has been used as a slimming agent (Horner, 1942). This, and certain basic dyes inhibit oxidative metabolism and result in a lowering in intraocular pressure. Sodium iodoacetate (Cibis, Constant, Pribyl, & Becker, 1957) appears to have direct effect on the retina, causing retinal degeneration and degeneration of nearly all tissues of the eye, including the lens. The cataract which results after injection of 20 to 60 milligrams of sodium iodoacetate per kilogram body weight resembles x-ray cataract. The drug is an enzyme inhibitor.

A variety of drugs can cause cataract (Bellows, 1944; van Heyningen, 1962). These include ergot, thallium, adrenaline, morphine-like drugs, and myleran. The latter is used in the treatment of myeloid leukemia. There are a number of hallucinogenic drugs which have stirred increased interest in recent years. Many of these have effects on visual experience. They have not been treated here because they are not, or should not, be potential stressors of operating personnel, and, in any case, there is very little information of a systematic sort on their effects.

THE VISUAL WORLD

Flash Blindness

A number of experiments have been performed to assess the effects of intense, short flashes of illumination on vision (Brown, 1964 b). Interest in this problem stems from the development of atomic weapons. An illustration of one experiment is provided in Fig. 9 (Brown, 1964 a). The upper graphs in the figure represent results with a criterion requiring one level of visual acuity.

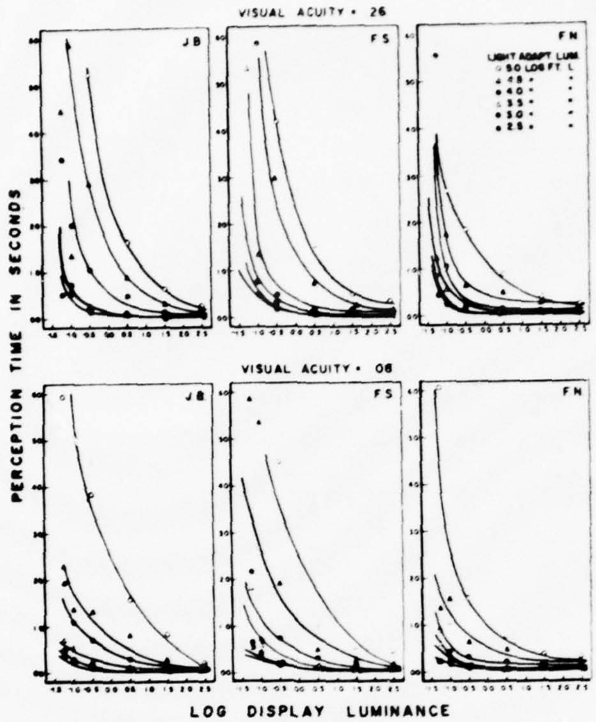


FIG. 9. Time required for identification of acuity gratings as function of grating luminance for each of six adapting luminances. Visual acuities of 0.26 and 0.08; subjects J. B., F. S., and F. N. (Brown, 1964a).

The lower graphs show a different, visual acuity requirement. Data are presented for each of three subjects. It is of interest to note that the least experienced subject shows performance superior to that of the experienced subjects, where performance is measured in terms of time required for detection. In several experiments of this type, it has been found that, with increased experience, variability of the results is decreased; and at the same time, the average detection time for a given set of conditions may show a slight increase. In the experiment illustrated, the adapting flash was of one second (sec) duration. This relatively long duration was employed in the laboratory in order to compensate for the limited, maximum available flux density from the adapting flash lamp. The more experienced subjects probably received more complete radiation during the 1 sec exposure than did the inexperienced subject. The latter may have blinked, thus excluding some of the adapting flash energy prior to the termination of the flash. This would have resulted in a shorter time for

recovery from flash exposure, and would explain the shorter recovery times shown by this subject. These results may be compared with those which have been found for studies of the effects of hypoxia on visual function. In the latter, the less experienced the subject, the higher his threshold, and the more poorly he performs. This is generally attributed to the fact that there is some anxiety associated with breathing an oxygen-poor gas mixture. In inexperienced subjects, this anxiety is frequently associated with an increased level of motor activity, which results in higher oxygen requirements and, hence, a greater effect stemming from oxygen reduction.

An illustration of the way in which flash blindness may influence vision for various conditions is presented in Fig. 10. In

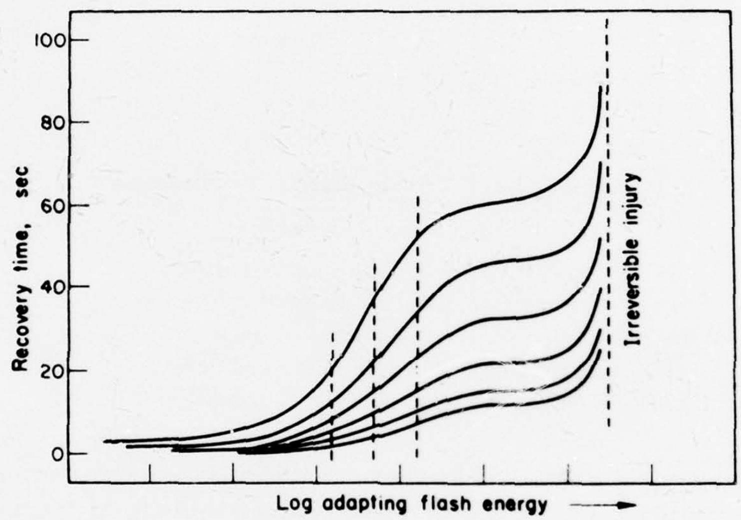


FIG. 10. Hypothetical relations between recovery time and adapting flash energy for each of six display luminances, increasing logarithmically from top to bottom (Brown, 1964b)

this illustration the ordinate axis shows recovery time measured to the point where a subject is capable of achieving a criterion visual function. The axis of abscissas illustrates the luminous energy within the adapting flash. A family of curves is presented for a series of different, criterion task illuminations, starting with the lowest level at the top and increasing task illumination in ratio steps from the top to the bottom curve. At low levels of adapting flash energy, recovery times are short for all task illuminations, approaching the minimum visual reaction time for the given task and the luminance employed. As adapting flash

energy increases, the recovery time increases, with the increase occurring at a greater rate, the lower the luminance of the criterion task. It is clear that the illumination provided for performance of a task may, in itself, provide a way in which flash blindness effects can be offset. When the level of illumination is sufficiently high, the duration of recovery is reduced to only a few seconds. At higher levels of adapting flash energy, the recovery time functions are shown to level out over a limited range of adapting flash energy. This kind of result appears in data of Hill and Chisum (1962), and of Whiteside (1960). Whiteside has interpreted this leveling to indicate a range in which energy has reached a value where bleaching is maximum. Under these circumstances, further increases in the adapting flash energy presented to the eye in a very short duration cannot cause further bleaching. Hence, such increases are not accompanied by further increase in recovery time. Beyond this range, the curves show a subsequent rising portion which is of the same form in the illustration for all of the criterion task luminances. Whiteside has suggested that, under extreme conditions, further increases in recovery time reflect the effects of reversible retinal injury. Recovery time is shown in this region to increase at an increasing rate. It approaches an asymptote in the region where energy becomes sufficiently high to cause irreversible injury. It must be emphasized that these relations are hypothetical. For obvious reasons, it has not been possible to do a complete study on human observers over a range of adapting flash energies which includes the region in which irreversible injury will occur. Most aspects of the form of the curves illustrated reflect results which have been obtained in individual experiments, however.

The problem of flash duration has not been considered. Variations in flash duration for a given amount of adapting flash energy may be accompanied by appreciable changes in recovery time. This matter has been discussed in detail in an earlier report (Brown, 1964b).

Ionizing Radiation

Ionizing radiation is not, strictly speaking, an element of the visual world, since it is not an appropriate stimulus for vision. Nonetheless, it is reasonable to consider it in conjunction with the problem of flash blindness. As a matter of fact, ionizing radiation is probably not a serious problem as a visual stress. At high levels, its effects on other than the visual system will

be of most significance, and at low levels it probably will not cause serious difficulty. It has been demonstrated that exposure to ionizing radiation can cause cataract. It may also reduce visual sensitivity by direct or indirect action in bleaching the photosensitive substance of the eye (Lipitz, 1955).

Flicker Effects

It has long been recognized that a slowly flickering light may be a cause of considerable irritation (Bach, 1957). Maximum annoyance seems to be associated with a rate of 3 to 6 flashes per sec. At a rate of approximately 9 flashes per sec, a flickering light may induce some drowsiness. At this frequency, the phenomenon of brightness enhancement appears to be a maximum (Brown, 1965b). A variety of subjective effects may be induced by flickering light of frequencies as high as 20 flashes per sec (Brown, 1965b; Smythies, 1957). These include the visualization of a variety of patterns, photic driving of the alpha rhythm, and induced seizures. Some of the studies of subjective irritation induced by flickering lights of very low frequency have found the amount of irritation to be increased with a decrease in the duration of the light flash for a given flash frequency. The shorter the flash duration, the more nearly the flashing source acts as a strobe light. A flashing light of very short duration presented at a low frequency results in a sequence of motionless scenes something like early motion pictures, but at a much slower rate. Some of the difficulty encountered in the performance of motor tasks under these circumstances may be related to problems which have been observed with delayed visual feedback (Smith, McCrary, & Smith, 1960). If the interval between flashes is sufficiently long, the observer may have difficulty in some kind of intellectual process of interpolating perceptions of continuous motion.

The subjective fusion of apparent flicker of a flashing light source has been employed as a measure of the effects of stress in a variety of situations (Simonson & Brozek, 1952). The flicker fusion frequency has been suggested by a number of investigators as an index of the effects on the central nervous system of both physical and mental activity.

Extensive Use of the Eyes

It is common knowledge that the eyes become fatigued by prolonged or excessive use. The result may be headache, or reduced coordination of extraocular musculature. There is little

evidence for any peripheral retinal fatigue effects. Effects are, probably, predominantly motor and central. Individual variability in susceptibility to this kind of stress is so great that it is not possible to make any generalizations concerning these effects.

Other Factors

A variety of other stressing situations may be added as contributory to visual stress without detailed explanation. These include such things as glare, whiteout, night myopia, and empty field myopia. The latter two are sometimes considered related, but they represent quite different effects. Night myopia has been described in detail by O'Brien (1953), and empty field myopia has been described by Whiteside (1957). Spectrally selective lighting may also cause visual stress. This is clearly apparent with the use of red light, which grossly alters normal contrast relations in a natural scene. The unusual contrast relations render the use of red goggles disturbing, and has limited pilot acceptance of these as protective devices (Brown, 1965a).

REFERENCES

Alpern, M. Movements of the eyes. In H. Davson (Ed.), The eye. New York: Academic Press, 1962. Pp. 135-136. (Part I, Vol. 3.)

Bach, L. M. R. (Ed.) ERDL-Tulane symposium on flicker. New Orleans: Tulane Univer. & USA Engr. Res. & Develpm. Labs., 1957. (April 6)

Becker, B. Decrease in intraocular pressure in man by a carbonic anhydrase inhibitor, Diamox. Amer. J. Ophthal., 1954, 37, 13-15.

Bellows, J. S. Cataract and anomalies of the lens. London: Kimpton, 1944.

Berger, C., McFarland, R. A., Halperin, M. H., & Niven, J. I. The effect of anoxia on visual resolving power. Amer. J. Psychol., 1943, 56, 395-407.

Brown, J. L. Acceleration and human performance. In W. Sinaiko (Ed.), Selected papers on human factors in the design and use of control systems. New York: Dover Publications Inc., 1961. Pp. 150-173. (a)

Brown, J. L. The physiology of acceleration-performance. In O. Gauer & G. Zuidema (Eds.), Gravitational stress in aerospace medicine. Boston: Little, Brown & Company, 1961. Pp. 90-114. (b)

Brown, J. L. Time required for detection of acuity targets following exposure to short adapting flashes. J. engrng Psychol., 1964, 3, 53-71 (a).

Brown, J. L. Experimental investigations of flash blindness. Human Factors, 1964, 6, 503-516. (b)

Brown, J. L. Flash blindness. Amer. J. Ophthal., 1965, 60, 505-519. (a)

Brown, J. L. Flicker and intermittent stimulation. In C. H. Graham (Ed.), Vision and visual perception. New York: Wiley. 1965. (b)

Brown, J. L., & Burke, R. E. The effect of positive acceleration on visual reaction time. J. aviat. Med., 1958, 29, 48-58.

Brown, J. L., Hill, J. H., & Burke, R. E. The effect of hypoxia on the human electroretinogram. Amer. J. Ophthal., 1957, 44, 57-67.

Cibis, P. A., Constant, M., Pribyl, A., & Becker, B. Ocular lesions produced by iodoacetic acid. AMA Arch. Ophthal., 1957, 57, 508-519.

Clark, B. Visual space perception as influenced by unusual vertibular stimulation. Human Factors, 1963, 5, 265-274.

Coburn, K. R., Beckman, E. L., & Duane, T. D. Limitation of ocular motility under acceleration: an objective endpoint for use with human centrifuge subjects. Aerospace Med., 1963, 34, 824-825.

Cusick, P. L., Benson, O. O., & Boothby, W. M. Effect of anoxia and of high concentrations of oxygen on the retinal vessels. Rochester, Minn: Proc. Staff Meeting Mayo Clinic, 1940, 15, 500.

Dautrabande, L., & Haldane, J. S. The effects of respiration of oxygen on breathing and circulation. J. Physiol., 1921, 55, 296.

Duane, T. D. Observations on the fundus oculi during blackout. AMA Arch. Ophthal., 1954, 51, 343-355.

Faucett, R. E. The effect of dramamine on visual and auditory acuity. USN Submarine Base, New London: med. res. lab. Rep., 1953, No. 222. (April)

Gallagher, T. J., Mammen, R. E., Nobrega, F. T., & Turaids, T. The effects of various oxygen partial pressures on scotopic and photopic vision. Johnsville, Pa.: USN Air Engng Cent. Rep., 1965, No. NAEC-ACEL-530.

Graybiel, A., & Hupp, D. The oculogyral illusion: a form of apparent motion which may be observed following stimulation of the semicircular canals. J. aviat. Med., 1946, 17, 3-27.

Guedry, F. E., Peacock, & Cramer, R. L. Nystagmic eye movements during interacting vestibular stimuli. Fort Knox: USA Med. res. Lab. Rep., 1957, No. 275.

Hardy, J. D. Acceleration. In J. D. Hardy (Ed.), Physiological problems in space exploration. Springfield: Charles C. Thomas, 1964, Pp. 152-195.

Hecht, S., Hendley, C. D., & Frank, S. The effect of anoxia on visual contrast discrimination. U.S. Nat. res. Council, Washington: Comm. av. Med. Rep., 1943, No. 184.

Hill, J. H. The effect of oxygen deprivation on the X-wave and B-wave of the human electroretinogram. USN Air Develpm. Cent. Johnsville Pa.: Av. med. Accel. Lab. Rep., 1965, No. NADC-MA-6008.

Hill, J. H., & Chisum, Gloria T. Flash blindness protection. Aerospace Med., 1962, 33, 958-964.

Horner, W. D. Dinitrophenol and its relation to formation of cataract. AMA Arch. Ophthal., 1942, 27, 1097-1121.

Klein, S. J., Wapner, S., Shaw, W. A., Cohen, M. M., & Werner, H. The relationship between muscle action potentials (MAP) and the perception of verticality. Paper read at Amer. psychol. Assoc., California, September, 1964.

Lagerwerff, J. M. Space cabin atmosphere trace contaminants and their possible influence on visual parameters. Human Factors, 1953, 5, 285-293.

Lewis, D. H., & Duane, T. D. Electroretinogram in man during blackout. J. appl. Physiol., 1956, 9, 105-110.

Lipitz, L. E. Electrophysiology of the X-ray phosphene. Radiat. Res., 1955, 2, 306-329.

Mackworth, N. H., & Winson, F. H. Effects of benzedrine sulphate on a visual vigilance test. Cambridge, G. B.: APRU Rep., 1947, No. R.N.P. 47/401, O.E.S. 129.

McFarland, R. A. Human factors in air transportation: occupational health and safety. New York: McGraw-Hill Co., 1953.

McFarland, R. A., & Evans, J. N. Alterations in dark adaptation under reduced oxygen tensions. Amer. J. Physiol., 1939, 127, 37-50.

McFarland, R. A., Halperin, M. H., & Niven, J. I. Visual thresholds as an index of physiological imbalance during anoxia. Amer. J. Physiol., 1944, 142, 328-349.

McFarland, R. A., Roughton, F. J., Halperin, M. H., & Niven, J. I. The effects of carbon monoxide and altitude on visual thresholds. J. aviat. Med., 1944, 15, 381-394.

Noell, W. K. Visual cell effects of high oxygen pressure. Fed. Proc., 1955, 14, 107.

O'Brien Brian. A study of night myopia. WAFB: WADC tech. Rep., 1953, No. WADC-TR-53-206.

Pigg, L. D., & Kama, W. N. The effect of transient weightlessness on visual acuity. WAFB: WADC tech. Rep., 1961, No. 61-184.

Rowland, L. S. Sulfa drugs and dark adaptation. Randolph Field, Tex.: Sch. av. Med. Rep., 1942, No. 2. (Proj. 91)

Simonson, E., & Brozek, J. Flicker fusion frequency: background and applications. Physiol. Rev., 1952, 32, 349-378.

Simonson, E., Brozek, J., & Keys. A. Effect of meals on visual performance and fatigue. J. appl. Physiol., 1948, 1, 270-278.

Smith, W. M., McCrary, J. W., & Smith, K. U. Delayed visual feedback and behavior. Science, 1960, 132, 1013-1014.

Smythies, J. R. A preliminary analysis of stroboscopic patterns. Nature, 1957, 179, 523-524.

Teare, R. J., & Parks, D. L. Visual performance during whole-body vibration. Wichita, Kan.: Boeing Co. tech. Rep., 1963, No. 4, D3-3512-4.

van Heyningen, R. The lens. In H. Davson (Ed.), The eye. New York: Academic Press, 1962. Vol. 1, Ch. 5, Pp. 268-271.

von Egmond, A. A. J., Groen, J. J., & Jongkees, L. B. W. The mechanics of the semicircular canal. J. Physiol., 1949, 110, 1-17.

Wald, G., Harper, P. V., Goodman, H. C., & Krieger, H. P. Respiratory effects upon the visual threshold. J. gen. Physiol., 1942, 25, 891-903.

White, W. J. Visual performance under gravitational stress. In O. H. Gauer & G. D. Zuidema (Eds.), Gravitational stress in aerospace medicine. Boston: Little, Brown, 1961. Pp. 70-89.

White, W. J. The effects of transient weightlessness on brightness discrimination. Douglas Missile & Space Systems Div. Paper. 1964. No. 3092.

White, W. J., & Monty, R. A. Vision and unusual gravitational forces. Human Factors, 1963, 5, 239-263.

Whiteside, T. C. D. The problem of vision in flight at high altitude. London: Butterworth's Scientific Publications. 1957.

Whiteside, T. C. D. The observation and luminance of a nuclear explosion. London: Air Ministry Flying Personnel Res. Comm. Rep., 1960, No. 1075. 1.

Wulfeck, J. W., Weisz, & Reb, M. W. Special factors influencing visual performance. 141-143. In Vision in military Aviation. WAFB: WADC tech. Rep., 1958, No. 58-399, 289-293. (a)

Wulfeck, J. W., Weisz, & Reb, N. W. Effects of vibration on visual performance. In Vision in Military Aviation. WAFB: WADC tech. Rep., 1958, No. 58-399, 289-293. (b)

Young, W. A., Shaw, D. B., & Bates, D. V. Presence of ozone in aircraft flying at 35,000 ft. Aerospace Med., 1962, 33, 311.

CLINICAL AND LABORATORY MEASUREMENT OF VISUAL FUNCTIONS OTHER THAN THE PREVIOUS TEN

SEEING—THE ENGINEER'S POINT OF VIEW

Richard Trumbull
Office of Naval Research

The visual system is one of man's most important means of contact with his environment. Determination of its capability and development of devices for such determination is a proper and challenging area of interest. Equally worthy of consideration is the functional employment of that capability. Here, one is faced with the fact that no system in man functions perfectly. In addition, vision is susceptible to distortions and illusions, which are normal. Its employment is characterized by other "normal" behavioral variables which are determined by habit, motivation, experience, and personality.

The system can be brought to bear on and to control the influences of these variables through training and deliberately introduced anti-distortion, real-world stimuli. This is an area which is in need of collation and emphasis. When engineers, designers, and others have to allow for natural propensities such as these, they require something other than handbook information on threshold, parallax, ERG, and quanta data. They have even a greater need to know about perception when they discuss detection, tracking, signal-to-noise ratios, and other areas in their fields. Further, while thresholds and sensory data might be required for initial selection, the perceptual mass developed through experience requires some other measures when the retention or the elimination of an experienced individual is concerned. This leads one to the interesting question of experience-control which really is the basic part of training. It is quite natural to ask if one with perfect vision can learn an operation which can continue to be performed later as visual acuity deteriorates. Is there not some way to provide perceptual training for someone with less

perfect visual capability initially? This reminds one of the World War II effort to see just how handicapped a person could be and still learn how to fly an airplane. Even as the military now seeks weapons which can continue to be used by a wounded or incapacitated man, one might ask how one would design a visual display compatible with increasing fatigue, loss of stereopsis, and other combat-incurred degradation. There are other searching questions arising from sensory (perceptual) deprivation-experiments. Could one design a non-flowable display panel for Hauty's pilots?

These questions are introduced now to raise the interest of the reader and invite him to join in a stimulating analysis of vision in operational contexts.

CONCLUDING REMARKS
by the
Chairman of the Symposium

Arthur Jampolsky
Institute of Visual Sciences, Presbyterian Medical Center
San Francisco

GENERAL CONCLUSIONS

It has been the purpose of this symposium to attempt to focus sharply on (a) the type of visual parameters to be considered, and (b) the scientific basis for the practical tests to be selected, and (c) the methods of quantifying or grading the test results.

From the impressive array of laboratory tests, it should be possible to extract clinically applicable test-procedures, with appropriate scoring or grading, for use by professional or technical personnel, or machine devices.

The following is the Chairman's brief view of some of the common denominators, points of disagreement, and general concepts which were expressed during the meeting and discussion periods.

The needs for a visual classification system are very real. It was recognized that the composition of the Committee on Vision was broadly based enough so that it should and could respond, in a practical way, to the needs of the agencies and services.

The rather confining ground rules stated in the introduction necessarily elicited some disquieting feelings (depending on one's orientation and background) relative to the uncomfortable, compromised conclusions reached. It is relevant to note here that the concluding discussion consisted of the expression of concern by two eminent veteran members of the Committee on Vision— that unless one specified the uses for which the test or grading was performed one could not properly describe the test or decrements of fitness for each visual parameter. It was countered that such a traditional view, of beginning with specific uses,

brought one the full circle back toward validation procedures, and the setting of standards as a beginning rather than as an intended end. If one begins with specific uses, one necessarily ends with validation of standards.

In order to appreciate fully the present direction, that of describing tests and graded results with regard only to general purposes and uses, the reader is invited to study the report of Working Group 20, which describes the role of the visual scientist. There was unanimous agreement among all of the consultants and members of Working Group 20 that validation of visual standards in terms of performance was costly, usually unnecessary, of questionable objectivity, and of questionable validity in regard to the methods for validation, and was not recommended as a solution to the widespread problems.

Admittedly, the alternative view of generality of uses necessitates an uncomfortable compromise with judgmental decisions relative to the type of tests to be recommended, and the grading score for the tests. The discussion established agreement that the grading scores were purely arbitrary, were to be considered as labels, and had no necessary implication relative to standards or limits; and that the recommended tests would describe the capabilities in the concerned visual function per se without implying that the score of the tested function necessarily related to detection of some other visual parameter. The information from the testing procedures would be expressed in terms of grades of visual fitness. The admittedly compromised result may then be used for general visual classification purposes, by anyone with the need, with the flexibility to alter judgments regarding standards for selection, placement, or retention, which may be altered as the circumstances demand. In this way, the role of the visual scientist can best be fulfilled. The participant members are to be congratulated on their responsiveness to the format which sometimes required a gentle coercion or a simple threat.

The following summary of the specifics is intended only to hit the high spots in order to give the sense of the presentations, and of the oral and written discussions. It will be the responsibility of the core-group team, augmented by appropriate experts, to establish judgmentally selected, practically useful tests and judgmentally graded decrements in order to fulfill the stated purpose of a matrix of grades of visual fitness for the visual apparatus which will be flexible and adaptable for whoever wishes to use it, for whatever performance task, with whatever changes and later constructed standards might seem appropriate, at whatever time.

SPECIFIC CONCLUSIONS

Visual Acuity

Tests should be performed under a lighted surround with or without habitual optical correction in order to elicit the vision "the subject lives with."

The Armed Forces Vision Tester is a machine adaptable for technicians' uses, or automation, and utilizes available, acceptable cards (Sloan) and should incorporate the newer concepts of letter spacing relative to letter size (contour interraction).

There are no practical objective substitutes for subjective visual acuity testing.

Grading of results should be in terms of visual angle, in 10 logarithmic decrements. Previous Vision Committee recommendations of logarithmic decrements may be updated to recognize the stated need for more sensitive grading around the 20/20 range, with the other convenient limit set at 20/200 (legal blindness). There need not be equal logarithmic decrements.

One may predict a visual acuity decrease with age, primarily due to intraocular pathology such as cataracts, change in pupil size, vascular defects, etc. Recognition of the predictive value of change in visual acuity associated with other parameters which are measured, such as refractive error state, age, and accommodative amplitude, would obviate an important problem of retention and waivers. The information-user should be well aware of the predictive value of these correlations, and it is the duty of the visual scientist to point these out.

There are no practical, useful, training techniques which will significantly improve visual acuity.

Refractive Error

The recommended test is retinoscopy with the aid of an appropriate lens bar. It was recognized that this technique requires professional skill, with appropriate assistants to aid in the flow of the subject traffic.

The machine assessment of refractive errors offers an objective method suitable for technicians or machine automation (the Fincham Optometer, or other electronic optometers).

The panelists carefully pointed out the difference between the refractive error state per se, and, on the other hand, the refractive error correction that might be used to correct refractive error symptoms.

The discussion brought out the points that the usual subjective

determination of the refractive error often is influenced by the use to which the numbers will be put, as well as a consideration of cycloplegia screening. It was agreed, however, that a number representing the refractive error of each eye per se could be determined by either a skilled, professional screener using retinoscopy, by technicians, or by automated machines utilizing the optometer principles. The future potential of later determination of refractive errors was also discussed.

Grading of refractive errors requires consideration of several numbers making up the characteristics of a given refractive error, such as the sphere, cylinder, axis, and right or left eye.

The panelists offered a unique and valuable suggestion, whereby a complex refractive error could be reduced to three values: (a) right eye, (b) left eye, and (c) the difference between the two eyes. These values could be utilized for the right-eye fitness, or both-eyes fitness. If necessary, this could be still further reduced to a single number describing the binocular refractive error status which would incorporate the anisometropia.

The prediction of change in refractive error for near-fixation objects as a result of presbyopia may be made with some reliability when correlated with age, visual acuity, and accommodative amplitude.

The following predicted changes in refractive error may be anticipated: 0-10 years—decrease in hyperopia; 10-20 years—increase in myopia; 20-40 years—increase dispersion; 40-60 years—increase in hyperopia and astigmatism; 60-80 years—increase in myopia.

Training techniques do not significantly affect the refractive error. This clear expression of agreement is worthy of emphasis.

Color Vision

The recommended test is the Farnsworth-Munsell 100 Hue Test which sensitively grades color defects.

An ingenious machine-testing device, easily automated for scoring, was suggested, which consists of rotating color-wheels.

The discussion brought out the fact that such a two-wheel testing device had been proposed many years ago, and a re-examination of its practical use is warranted.

Grading of color deficiencies into ten decrements was reluctantly but cheerfully offered by the panelists.

Distance Vision

Distance vision and depth perception were deemed inappropriate terms since they are composed of highly complex factors with no appropriate tests possible. Rather, it was agreed that the term stereopsis, defined in terms of retinal disparity, is a quantitatively measurable parameter. Stereopsis is a recommended re-title of this visual parameter.

A machine-testing device, the Armed Forces Visual Tester, is available with acceptable screening cards. This machine-device is suitable for professional or technical personnel, or automation.

Grading should be done in terms of parallactic angle (rather than percentage of stereopsis) and expressed on a log scale. The previous work of Fry and Shepard with such a scoring was made so as to be useful in terms of the compensation scale of the American Medical Association.

An alternative machine device, the Verhoeff Stereopter, is also suitable for use by a technician or by automation. In its present form the monocular clues are excessively weighted, and a modification of equal-width bars is available and adaptable for screening purposes.

One may predict some decrement of stereopsis with age, primarily due to decreases in visual acuity and image blur.

Training, or enhancement of the quality or degree of stereopsis, is possible if the stereoscopic percept is present at all.

A demonstration of the stereoscopic percept is advisable before subject-testing.

Heterophoria and Ocular Rotations

Since the term heterophoria is limiting, it was suggested that the term binocular coordination may better describe the objectives of simultaneous consideration of heterophoria and ocular rotations.

The preferred test for the motor deviation (basic deviation) is the applied, psychophysical, subjective determination by white Maddox rod, with a brief, flash exposure of the line image, for both distance and near fixations, with good accommodative stimulus control. The zero points should be randomized.

The test for fixation disparity reflects the motor imbalance during fusion, which could be compared with the motor imbalance when fusion is disrupted.

The test objective should be to determine if fusion is present, and how well the two eyes are coordinated. The test to determine if fusion is present is implicit in the determination that no deviation exists for the primary positions. The four-prism diopter test was suggested as a supplementary test for this assessment.

The binocular coordination test could be assessed by measuring the recovery point of fusional amplitude, and by ocular rotations which should be expressed in prism-diopter decrements of difference from the primary position deviation.

Machine automation is possible for the recommended tests. It was recommended that the many variables in the testing situation could best be controlled by machine-testing, which Dr. Sloan has shown to have good correlation with non-machine tests.

Grading of fusion status (presence or absence of bifoveal fusion) may be made on a pass-fail score. The deviation in the primary positions (latent or manifest deviations) could be expressed in prism-diopter decrements for both the horizontal and the vertical meridians. Ocular rotations elicit differences from the primary position deviation, expressed in prism-diopter decrements.

There is no predicted significant change in these assessments with age, except for some deficient upgaze capability, and for some anticipated shift in near phoria at the pre-presbyopic and post-presbyopic ages.

Training, or enhancement of the security of fusion lock, is possible by anti-suppression orthoptics, or by increasing the fusional amplitudes. There is questionable maintenance of these enhanced capabilities.

Accommodative Amplitude

The suggested test is the "push up" determination for each eye of the nearest point where print of a designated size can be read. This test is adaptable for professional-technical personnel, or machine automation.

Electronic optometers, which accurately measure changes of accommodation, and which attain maximum efficiency with solid state components, were described.

Also described were ultrasound techniques for the assessment of accommodative changes.

Grading of accommodative amplitude in one-diopter decrements was suggested. It was pointed out that the accommodative unit is dependent on whether a correction is or is not worn during the test.

There is good prediction of the anticipated change in the accommodative amplitude with age. This, of course, may again be fruitfully correlated with other factors such as refractive error, distance and near visual acuity, etc.

Visual Fields

The tests of practical usefulness are: (a) the finger-confrontation field determination, especially for gross temporal field defect; and (b) the Harrington-Flocks Multiple Pattern Field Screener. The latter may be utilized by technicians, or automated. The discussion brought out that this multiple-pattern screen device utilizes Bender's concept of simultaneous, bilateral field stimulation, which results in the detection of a large number of false positives.

Grading is suggested on the basis of pass-fail (no defect—any defect) insofar as detection-referral grading is concerned. A secondary grading system should be derived from careful, clinical, subjective field-testing in order to describe the type and severity of field defect relative to the possible importance or unimportance of the detected defect.

Objective electroperimetry is, at present, a laboratory tool requiring further refinement and validation before it may be used as a screening device, or as a clinical instrument. It offers much promise for future laboratory and clinical usefulness.

Night Vision

There was considerable discussion regarding the complicated nature of night vision, and the fact that no simple index fully characterizes this complex function.

The recommended test is of dark adaptation and rod vision. The Army Night Vision Tester is available for this purpose, but has not enjoyed wide acceptance. It employs a short (five minute) testing procedure at a selected mesopic level. The discussion pointed out that superior, as well as inferior, capability could and should be detected by present testing techniques, and that these needs might be met by tests made at different mesopic levels.

It was suggested that separate consideration might be given to the parameter of glare resistance.

Intraocular Tension

The test of intraocular tension can practically be made in approximately one minute by utilizing (a) the Mackay-Marg Elec-

tronic Recording Tonometer, or (b) the hand-held Goldmann Tonometer, or (c) the Schiotz Indentation Tonometer. These instruments can be utilized by professional or trained technicians, preferably with the use of corneal anesthesia for more reliable test scores.

Grading of the intraocular tension can be made in terms of three groups, (a) pressure too low, (b) pressure in safe range, and (c) pressure too high. Or, grading could be on a scale of millimeters of mercury from 0 to 45.

The test purpose is to detect those with the glaucoma syndrome, and to detect those who may develop glaucoma. It was emphasized that a single, intraocular tension measurement for the test of glaucoma does not detect 40 per cent of those who have glaucoma. As a predictor of glaucoma, a single, intraocular tension determination lacks scientific validity.

The discussion brought out that an elevated tension is a reliable predictor of glaucoma, even though presently lacking statistical confirmation. It was agreed that the intraocular tension per se does not characterize the glaucoma syndrome, but that other visual defects are required to establish the diagnosis.

The value of the test utilizing a single, intraocular tension determination as a detector or predictor of glaucoma was left an open question. This matter is to be further pursued and reevaluated by the core group and by the experts charged with the investigation of this visual parameter.

Stress Tolerance

The panelists expressed an unwillingness to define the term "stress." The discussion elicited an alternative suggestion of "vision in unique environments."

Obviously, there is no recommended test which could be considered all-inclusive. There was a discussion of direct and indirect visual consequences of the different stresses, such as acceleration, vibration, high and low oxygen tensions, structureless fields of different types, anxiety, and other psychological factors. It was emphasized that one stress may augment or negate another stress.

It was suggested that stress factors should be assessed in a situation as similar as possible to the complex, real situation. Simulated testing situations were discussed along with the many unknown and known interactions.

Seeing, The Engineer's Point of View

This stimulating analysis of vision in operational context went to the core of the problem toward which this symposium was directed, namely, that of stimulating the interest of visual scientists in bringing their various disciplines to bear upon the solving of practical, operational problems.

The point was made that the measured eye is not necessarily the operating or functioning eye. The functional employment of the visual capability is worthy of consideration, and development of devices for such determination is challenging and appropriate.

Unique tests requiring other than the usual and traditional measurement techniques will be necessary to get at the knotty problem of perception, and the perceptual mass developed through experience, in order to assess adequately the visual capabilities of detection, tracking, etc.

This led to a discussion of the question of experience control, which really is the basic part of training. Is perceptual training possible and feasible?

It was pointed out that an additional responsibility of the "core group" selected to compose the matrix of visual fitness, will be to explore the need to list visual parameters other than the traditional ones discussed at this symposium, to describe tests, and to define grading scores for them.

In conclusion, the chairman wishes to thank the participants for bringing their skills and advice to bear upon these practical problems. He wishes also to thank the members and guests of the Committee on Vision for their expressed comments, suggestions, and criticisms, and requests that their continued expressions be sent to the Executive Secretary of the Committee on Vision for consideration by the continuing working groups.

This symposium was a test of the adaptive qualities of the participating scientists representing many different capabilities who have responded to the real needs of the services and agencies who collectively support these meetings and efforts.

One gains the impression that machine-testing, preferably automated, has the outstanding advantage of standardizing the testing variables. Maximally automated records of machine-testing would assure that selected tests are done, and done adequately, if the machine devices are practical and available.

The core groups, appropriately augmented by selected experts, will assimilate, sharpen, and further define the results of these

combined efforts, and the conclusions thus derived from this symposium will form the basis for implementing the concept of visual fitness as a flexible, visual classification system for general use in the spectrum of performance tasks from flying, to driving, to cooking.